Matter matters

Circular economy and equity in materials for renewable electricity

GEORGIA SAVVIDOU

THESIS FOR THE DEGREE DOCTOR OF PHILOSOPHY

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GEORGIA SAVVIDOU

Department of Environmental and Energy Sciences

CHALMERS UNIVERSITY OF TECHNOLOGY

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Department of Environmental and Energy Sciences
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

Cover: Painted by Panayiota Markou. At a time of rapidly growing AI-generated imagery, I asked my niece to paint the cover. I shared the themes of the work with her and invited her to interpret them freely through an abstract painting. I am deeply grateful that she did.

The artwork was envisioned around the idea of circularity, with visual elements suggesting cyclical movement, the interaction between wind and sunlight, and a contrast between subsurface material extraction and surface-level renewable electricity production. Earth-toned colours transition into greens, blues, and yellows, reflecting both material foundations and the energy transition.

All photographs of wind tubines and solar panels were taken either by the author or by close friends and family, in Cyprus, the Netherlands, Denmark, and Sweden. Photo credits: Photo 1: Susana Tecante; Photo 2: Anders Johansson; Photo 3: Mikael Wernersson; Photo 4: the author; Photo 5: Christiana Savvidou; Photo 6: the author; Photo 7: Helena Cedergren; Photo 8: Savvas Savvides; Photos 9–10: Mikael Wernersson.

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ABSTRACT

Mitigating human-induced climate change requires large-scale deployment of renewable electricity technologies such as wind and solar power. However, the material supply chains underpinning these technologies pose environmental, climate, and social challenges and raise questions about the feasibility and equity of allocating available materials. In this context, the circular economy is increasingly explored as a means to address material demand and supply challenges and to support deployment at the scale and pace required to meet climate targets.

This thesis develops a dynamic material flow analysis model combined with explorative scenario development to assess the effects of circular economy strategies on material demand and embodied emissions. Furthermore, it introduces a framework that integrates the model with the operationalization of selected equity principles to evaluate whether material supply requirements, and their reduction through circular economy strategies, align with equitable material allocation. The model is applied to wind and solar power deployment within Swedish and European Union decarbonization scenarios to 2050. Four circular economy strategies are considered: longer service lifespans, material intensity reduction, substitution, and recycling. Steel and concrete are included to assess circular economy effects on embodied emissions, and minor metals and rare earth elements to evaluate effects on material demand, supply, and equity.

The results show that, while circular economy strategies reduce embodied emissions, transformative changes in steel and cement production remain necessary to achieve substantial reductions. For minor metals, material intensity reduction and substitution have the greatest potential to reduce total demand and associated supply requirements, with immediate effects that make them particularly relevant in the early and middle stages of the energy transition. In contrast, recycling and longer service lifetimes have more delayed effects. Results also vary across metals, with substantial differences in the compatibility of required supply with allocation based on equity principles. Overall, the effectiveness of circular economy strategies is time-, metal-, technology-, and market-share-dependent, indicating that no single strategy fits all contexts and that tailored portfolios are needed. A trade-off emerges within the transition period: strategies that most reduce gross metal demand can increase primary demand, requiring choices between minimizing total material throughput and reliance on primary supply. While the joint implementation of circular economy strategies reduces cumulative primary demand across metals by more than half and alleviates pressure on supply systems, high primary demand persists for most metals through 2050. For some metals, required supply exceeds allocation based on equity principles even under ambitious circular economy implementation.

Overall, the findings show that circular economy strategies are necessary but not sufficient to eliminate primary extraction and achieve equitable material allocation. Complementary measures are required, which may include further material demand reductions, energy demand reduction, stronger governance, and a broader reconsideration of energy transition objectives.

Keywords: Circular economy, Renewable electricity, Wind, Solar, Material flow analysis, Primary demand, Secondary supply, Equity, Equitable allocation, Equity principles

ΠΕΡΙΛΗΨΗ

Η αντιμετώπιση της ανθρωπογενούς κλιματικής αλλαγής απαιτεί την εκτεταμένη ανάπτυξη τεχνολογιών ανανεώσιμης ηλεκτρικής ενέργειας, όπως η αιολική και η ηλιακή ενέργεια. Ωστόσο, οι εφοδιαστικές αλυσίδες υλικών που στηρίζουν αυτές τις τεχνολογίες δημιουργούν περιβαλλοντικές, κλιματικές και κοινωνικές προκλήσεις και εγείρουν ερωτήματα σχετικά με την εφικτότητα και τη δικαιοσύνη στην κατανομή των διαθέσιμων υλικών. Σε αυτό το πλαίσιο, η κυκλική οικονομία διερευνάται όλο και περισσότερο ως μια προσέγγιση για την αντιμετώπιση των προκλήσεων που σχετίζονται με τη ζήτηση και την προσφορά υλικών και για την υποστήριξη της ανάπτυξης στον βαθμό και με τον ρυθμό που απαιτούνται για την επίτευξη των κλιματικών στόχων.

Η παρούσα διατριβή αναπτύσσει ένα δυναμικό μοντέλο ανάλυσης ροών υλικών σε συνδυασμό με διερευνητική ανάπτυξη σεναρίων, προκειμένου να αξιολογήσει τις επιδράσεις των στρατηγικών κυκλικής οικονομίας στη ζήτηση υλικών και στις ενσωματωμένες εκπομπές. Επιπλέον, εισάγει ένα πλαίσιο που συνδυάζει το μοντέλο με την πρακτική εφαρμογή επιλεγμένων αρχών ισότητας, ώστε να αξιολογηθεί κατά πόσο οι απαιτήσεις προσφοράς υλικών, καθώς και η μείωσή τους μέσω στρατηγικών κυκλικής οικονομίας, ευθυγραμμίζονται με μια δίκαιη κατανομή των υλικών. Το μοντέλο εφαρμόζεται στην ανάπτυξη αιολικής και ηλιακής ενέργειας σε σενάρια απανθρακοποίησης της Σουηδίας και της Ευρωπαϊκής Ένωσης έως το 2050. Εξετάζονται τέσσερις στρατηγικές κυκλικής οικονομίας: η παράταση της διάρκειας ζωής, η μείωση της έντασης υλικών, η υποκατάσταση και η ανακύκλωση. Το σκυρόδεμα και ο χάλυβας περιλαμβάνονται για την αξιολόγηση των επιπτώσεων στις εκπομπές, ενώ δευτερεύοντα μέταλλα και στοιχεία σπάνιων γαιών εξετάζονται για την αξιολόγηση των επιπτώσεων στη ζήτηση, την προσφορά και τη δικαιοσύνη.

Τα αποτελέσματα δείχνουν ότι, ενώ οι στρατηγικές κυκλικής οικονομίας μειώνουν τις ενσωματωμένες εκπομπές, μετασχηματιστικές αλλαγές στην παραγωγή χάλυβα και τσιμέντου παραμένουν απαραίτητες για την επίτευξη ουσιαστικών μειώσεων. Για τα δευτερεύοντα μέταλλα, η μείωση της έντασης υλικών και η υποκατάσταση παρουσιάζουν το μεγαλύτερο δυναμικό για μείωση της συνολικής ζήτησης και των σχετικών απαιτήσεων προσφοράς, με άμεσες επιδράσεις που τις καθιστούν ιδιαίτερα σημαντικές στα πρώτα και ενδιάμεσα στάδια της ενεργειακής μετάβασης. Αντίθετα, η ανακύκλωση και η παράταση της διάρκειας ζωής έχουν πιο καθυστερημένες επιδράσεις. Τα αποτελέσματα διαφέρουν επίσης μεταξύ των μετάλλων, με σημαντικές διαφοροποιήσεις στη συμβατότητα μεταξύ της απαιτούμενης προσφοράς και της κατανομής βάσει αρχών ισότητας. Συνολικά, η αποτελεσματικότητα των στρατηγικών κυκλικής οικονομίας εξαρτάται από τον χρόνο, το μέταλλο, την τεχνολογία και το μερίδιο αγοράς, γεγονός που υποδεικνύει ότι δεν υπάρχει μία ενιαία στρατηγική κατάλληλη για όλες τις περιπτώσεις και ότι απαιτούνται προσαρμοσμένα μείγματα στρατηγικών. Κατά τη διάρκεια της μετάβασης αναδεικνύεται ένας συμβιβασμός: οι στρατηγικές που μειώνουν περισσότερο τη συνολική ζήτηση μετάλλων μπορεί να αυξήσουν την εξάρτηση από πρωτογενή προσφορά. Αν και ο συνδυασμένος σχεδιασμός στρατηγικών κυκλικής οικονομίας μειώνει τη σωρευτική πρωτογενή ζήτηση για μέταλλα κατά περισσότερο από το μισό και περιορίζει τις πιέσεις στα συστήματα προσφοράς, η πρωτογενής ζήτηση παραμένει σε ψηλά επίπεδα για τα περισσότερα μέταλλα έως το 2050. Για ορισμένα μέταλλα, η απαιτούμενη προσφορά υπερβαίνει την κατανομή που προκύπτει από αρχές ισότητας ακόμη και υπό φιλόδοξη εφαρμογή στρατηγικών κυκλικής οικονομίας.

Συνολικά, τα ευρήματα δείχνουν ότι οι στρατηγικές κυκλικής οικονομίας είναι αναγκαίες αλλά όχι επαρκείς για την εξάλειψη της πρωτογενούς εξόρυξης και την επίτευξη δίκαιης κατανομής των υλικών. Απαιτούνται συμπληρωματικά μέτρα, τα οποία ενδέχεται να περιλαμβάνουν περαιτέρω μείωση της ζήτησης υλικών, μείωση της ενεργειακής ζήτησης, ισχυρότερη διακυβέρνηση και μια ευρύτερη επαναξιολόγηση των στόχων της ενεργειακής μετάβασης.

Λέξεις-κλειδιά: Κυκλική οικονομία, Ανανεώσιμη ηλεκτρική ενέργεια, Αιολική ενέργεια, Ηλιακή ενέργεια, Ανάλυση ροών υλικών, Πρωτογενής ζήτηση, Δευτερογενής προσφορά, Ισότητα, Δίκαιη κατανομή, Αρχές ισότητας

APPENDED PUBLICATIONS

This thesis is based on the following articles:

Article I Savvidou, G., Johnsson, F., 2023. Material Requirements, Circularity Potential and Embodied Emissions Associated with Wind Energy. *Sustainable Production and Consumption* 40, 471–487. https://doi.org/10.1016/j.spc.2023.07.012

Article II Savvidou, G., Johnsson, F., Ljunggren, M., Liu, Q., Tasseven, U., Zachariadis, T., 2026. Circular technology design and its potential influence on minor metals demand in wind and solar expansion. *Journal of Industrial Ecology.* https://doi.org/10.1007/s44498-026-00040-0

Article III Savvidou, G., Ljunggren, M., Johnsson, F., 2026. Slowing, narrowing, and closing material flows: Impacts on metal demands in wind and solar power. Sustainable Production and Consumption 64, 137–150. https://doi.org/10.1016/j.spc.2026.02.007

Article IV Savvidou, G., Ljunggren, M., & Johnsson, F. Metal availability and climate justice: assessing rare earth element demand in EU wind power transition against equity principles. Manuscript.

Author contributions

Article I: Georgia Savvidou conceived the idea and carried out methodology development, formal analysis, preparation of the results, and wrote the original draft. Filip Johnsson contributed to scientific discussions and reviewed the manuscript.

Article II: Georgia Savvidou conceived the idea and carried out methodology development, formal analysis, preparation of the results, and wrote the original draft. Qiyu Liu contributed with software support, method development, and reviewing. Filip Johnsson contributed to scientific discussions and reviewed the manuscript. Maria Ljunggren contributed to scientific discussions and reviewed the manuscript.

Article III: Georgia Savvidou conceived and developed the idea with support from Maria Ljunggren. Georgia Savvidou carried out methodology development, formal analysis, preparation of the results, and wrote the original draft. Filip Johnsson contributed to scientific discussions and reviewed the manuscript. Maria Ljunggren contributed to scientific discussions and reviewed the manuscript.

Article IV: Georgia Savvidou conceived the idea and carried out methodology development, formal analysis, preparation of the results, and wrote the original draft. Filip Johnsson contributed to scientific discussions and reviewed the manuscript. Maria Ljunggren contributed to scientific discussions and reviewed the manuscript.

OTHER PUBLICATIONS

Other publications by the author related to the thesis topic are listed below but are not included in the thesis because they fall outside its scope or overlap with the appended articles.

Journal articles

Lehtveer, M., Göransson, L., Heinisch, V., Johnsson, F., Karlsson, I., Nyholm, E., Odenberger, M., Romanchenko, D., Rootzén, J., **Savvidou**, G., Taljegard, M., Toktarova, A., Ullmark, J., Vilén, K., Walter, V., 2021. Actuating the European Energy System Transition: Indicators for Translating Energy Systems Modelling Results into Policy-Making. Front. Energy Res. 9, 677208. https://doi.org/10.3389/fenrg.2021.677208

Sharma, S. E., Das, R. R., Janzwood, A., Joshi, N., MacArthur, J. L., **Savvidou**, G., 2025. Equity, diversity and inclusion promises, exclusive practices? How to move towards effective and just energy transitions. *Energy Research & Social Science*, 120, 103935. https://doi.org/10.1016/j.erss.2025.103935

Tasseven, U., Zachariadis, T., Johnsson, F., **Savvidou**, G., Liu, Q., 2026. Assessing material requirements, supply and circularity potentials for photovoltaic systems – the case of Cyprus. Renewable Energy 256, 124357. https://doi.org/10.1016/j.renene.2025.124357

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Savvidou, G., 2024. Matter matters: Material Flow Analysis of Renewable Electricity Generation Technologies., *Chalmers University of Technology*

Conference papers and abstracts

Savvidou, G., Johnsson, F., 2023. Material requirements, circularity potential and greenhouse gas emissions associated with wind energy. Abstract presented at the *11th International Conference on Industrial Ecology (ISIE2023)*, Leiden, July 2-5.

Savvidou, G., Johnsson, F., Liu, Q., 2023. Bridging Climate and Circular Economy Related Policy Targets: Insights from Material Requirements in the Renewable Electricity System. *Proceedings of the 7th International Conference on Renewable Energy Sources and Energy Efficiency (RESEE2023),* Nicosia, 12-14 October (peer-reviewed). ISBN 978-9963-567-06-5, https://www.resee-cy.com/wp-content/uploads/2023/10/RESEE-2023-Book-of-Proceedings-October-2023.pdf

Savvidou, G., Ljunggren, M., Johnsson, F., 2025. Demand for minor metals in future wind and solar photovoltaic expansion: the role of circular economy. Abstract presented at *the International Round Table on Materials Criticality (IRTC) Conference: From Raw Material Policies to Practice*, Ljubljana, February 19-21.

Project reports and policy briefs	Johansson, N., C., Hansson, J., **Savvidou**, G., Johnsson, F., 2025. Kritiska metaller för energisystemets omställning – perspektiv på Sveriges behov med fokus på vindkraft och solceller (critical metals for the energy system transition – perspectives on Sweden's needs with a focus on wind power and solar cells). https://energiforsk.se/media/fpwbsv0r/kritiska-metaller-fo-r-energisystemets-omsta-llning.pdf
	Johansson, N., C., Hansson, J., **Savvidou**, G., Johnsson, F. Kritiska metaller inom energiomställningen – med fokus på vindkraft- och solcellsutbyggnad i Sverige utifrån ett behovs-, rättvise- och försörjningsperspektiv (Critical metals in the energy transition – with a focus on the expansion of wind power and solar photovoltaics in Sweden from a needs-based, justice, and supply perspective). In preparation.

ITHAKA

As you set out for Ithaka
hope your road is a long one,
full of adventure, full of discovery.
Laistrygonians, Cyclops,
angry Poseidon—don’t be afraid of them:
you’ll never find things like that on your way
as long as you keep your thoughts raised high,
as long as a rare excitement
stirs your spirit and your body.
Laistrygonians, Cyclops,
wild Poseidon—you won’t encounter them
unless you bring them along inside your soul,
unless your soul sets them up in front of you.

Hope your road is a long one.
May there be many summer mornings when,
with what pleasure, what joy,
you enter harbors you’re seeing for the first time;
may you stop at Phoenician trading stations
to buy fine things,
mother of pearl and coral, amber and ebony,
sensual perfume of every kind—
as many sensual perfumes as you can;
and may you visit many Egyptian cities
to learn and go on learning from their scholars.

Keep Ithaka always in your mind.
Arriving there is what you’re destined for.
But don’t hurry the journey at all.
Better if it lasts for years,
so you’re old by the time you reach the island,
wealthy with all you’ve gained on the way,
not expecting Ithaka to make you rich.

Ithaka gave you the marvelous journey.
Without her you wouldn't have set out.
She has nothing left to give you now.

And if you find her poor, Ithaka won’t have fooled you.
Wise as you will have become, so full of experience,
you’ll have understood by then what these Ithakas mean.

Constantine Peter Cavafy

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Over the past five years, my PhD journey has offered far more than what the book you have in your hands could ever convey. I have learned to embrace complexity, tolerate ambiguity, and develop self-awareness. I have grown both professionally and personally, in ways I never anticipated.

I recognize that my PhD journey is one full of privileges, many of which I may never fully understand. During my PhD journey, I had the honor of contributing to the latest IPCC report on Impacts, Adaptation, and Vulnerability. During that project I had to confront the fact that 'The world's poorest countries are expected to be hit hardest by climate change extremes …while their contributions to … causing global warming are among the lowest globally'. As a citizen of the Global North, I am deeply privileged. I have been pursuing my PhD while living in Gothenburg, where I live in proximity to the Sámi people and their Land. I am a PhD researcher at Chalmers University of Technology. I recognize the privilege that comes with being part of an internationally respected academic institution. Moreover, the economic and institutional support I receive as a European PhD student in Sweden, where a PhD is treated as full employment with all the associated benefits, is a privilege that few in academia enjoy. Not having to worry about my residency or citizenship status is another form of privilege. The security of having employment after completing my PhD is yet another significant advantage.

At the same time, privilege does not shield one from the toll that stress can take on the body. This PhD journey has taught me the importance of self-care, of striving for healthy work environment, and of creating a sense of belonging. It has also reminded me to take care of my body, heart, and spirit, while continuing to cultivate the mind.

Starting my PhD during the COVID-19 pandemic and not moving to Gothenburg until well within the first year of the program was not what I would call a smooth beginning to a PhD journey. My research at Chalmers has focused on the material requirements of the energy transition and the role the circular economy can play in reducing them. Through this work, I have developed a deeper understanding of the profound injustices embedded in the supply chains of highly valued materials, many of which are central to the energy transition.

The work presented in the final part of this thesis is closely connected to questions of international cooperation. At the same time, the course of this PhD has unfolded during a period marked by major global challenges that have placed significant strain on systems of international cooperation. Events such as the COVID-19 pandemic, wars, and even an ongoing genocide unfolding before our eyes have shaken my confidence in the ability of international cooperation structures to effectively advance collective processes such as the Paris Agreement and the Agenda 2030, or even, more broadly, global security.

Experiencing a loss of confidence in these systems has made it more difficult to sustain the motivation and mental strength needed to finalize this work. At the same time, over the course of this PhD, I have been deeply moved and inspired by individuals and movements within and beyond academia.

As I write this text and reflect on my PhD journey, it is time to express my gratitude to those who have helped me along the way.

Filip, thank you for the time, resources, and trust you invested in my research, and for the flexibility you offered along the way. Maria, thank you for coming into this journey along the way with genuine interest and for your support in helping me find a way forward when I needed it. I also want to express my gratitude to all my co-authors, for your insights and support.

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To my colleagues at EnTek, thank you for the fun discussions over lunch and the friendly encounters in the corridors. Thank you to my colleagues at ESA for welcoming me into your team, I was surprised at how quickly I felt at home, and that says a lot about the work environment you have created. To colleagues in both EnTek and ESA, thank you for the writing bubbles. If you are reading this and have a writing project, whether it is a PhD thesis, a book, or a paper, my unsolicited advice, if I may, is to join or organize a writing bubble.

There is a certain power in being in a room with others who are also focused on writing, removing distractions, and allowing yourself to write without interruption. It is the simple things that make big things happen.

Carl-Joar, Angelica, Leon, Maria, Elena, Rebecka, Vi, Kelsey, Achintya, Malin, Rana, Finja, Julia, Paul, and all new members and those to come, the Dr. Genie team and beyond, I feel honored to work with you on the important topics of equity, diversity, and inclusion at Chalmers and in academia. The fight for a more equitable academia, one free from discrimination and sexual harassment, is an ongoing one. I am in awe of your dedication to this cause. Your creativity, your solutions-oriented mindset, and your persistence truly inspire me. Lauri, thank you for helping us see one another and build trust, and for teaching us about leading with empathy, the power of influence, unconscious biases, and so much more. Maria Saline, every workplace needs a person like you. Your positivity and uplifting energy make difficult challenges feel lighter. Dr. Genie is one of the many seeds you have planted over the years, and one that has truly bloomed. I hope you feel as proud as I do.

To all members of the Women and Inclusivity in Sustainable Energy Research (WISER) steering committee during the time I was also part of it, I am proud of the work we accomplished together over those three years and of the events we organized. Being part of such an interdisciplinary network of scholars from around the world has been a rewarding journey, one that brought many learnings for which I am deeply grateful.

Μάμα και παπά, ε βάλατε τα θεμέλια για να φτάσω δαμέ που είμαι με τρόπους που ίσως να μεν κατανοήσω ποττέ πλήρως. Γι’ αυτό σας είμαι για πάντα ευγνώμων. Μάμα, η ανιδιοτελής σου αγάπη σημαίνει τα πάντα για μένα. Δεν σου δόθηκε η ευκαιρία για την εκπαίδευση που άξιζες, γι’ αυτό ήθελες να διασφαλίσεις ότι τζιαι οι τρεις μας εν να τελειώσουμε το πανεπιστήμιο. Με ένα μεταπτυχιακό δίπλωμα, ένα διδακτορικό και ένα ακόμη διδακτορικό καθ’ οδόν, νομίζω ε ξεπέρασες τον στόχο σου κατά πολύ! Παπά, η αγάπη σου για τη φύση, την καλλιέργεια της γης και της παραγωγής δικής σου τροφής εν κάτι που εν εκτίμησα όταν ήμουν παιδί, αλλά κάτι από το οποίο ελπίζω να συνεχίσω να εμπνέομαι τζιαι να μαθαίνω ως ενήλικας. Χριστιάνα, το αυθόρμητο τζιαι χαρούμενο σου πνεύμα στες κλήσεις μας υπενθυμίζει με να μεν παίρνω τον εαυτό μου τόσο στα σοβαρά. Ολυμπία και Παναγιώτα, οι ζωγραφιές σας στο γραφείο μου υπήρξαν καθημερινή έμπνευση για μένα. Το να σας βλέπω να μεγαλώνετε τζιαι να δημιουργείτε η κάθε μια το δικό της χαρακτήρα εν ένα μάθημα ζωής για μένα. Σάββα, το ότι έχω έναν αρφό που έκαμε διδακτορικό σημαίνει ότι ξέρω ποιον να πιάσω τηλέφωνο στην οικογένεια όταν χρειάζομαι κάποιον να με καταλάβει χωρίς να χρειαστεί να πω πολλά. Ακόμα ξαφνιάζει με πόσο παρόμοιες αντιδράσεις έχουμε σε κάποιες καταστάσεις, μα ε μεγαλώσαμε μαζί; ☺

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Kiriaka 🥁, thank you for showing me the power of community and creativity, and for showing what collective care can look like. There is a unique kind of power in creating music together, and in being part of a community grounded in shared values.

Thank you, nature.
“Those who contemplate the beauty of the earth find reserves of strength that will endure as long as life lasts. There is something infinitely healing in the repeated refrains of nature, the assurance that dawn comes after night, and spring after winter.”— Rachel Carson.

I want to end by saying that *it takes a village*. If I were to acknowledge everyone who has one way or the other been part of this journey, this section might end up longer than the thesis itself. But if you're reading this and your name isn't mentioned above, please know that I’m truly grateful.

Georgia Savvidou,
Gothenburg, 18th of May 2026

FUNDING

This work has been financially supported by the Swedish Energy Agency. In addition, financial support was provided by the Nepp research program.

USE OF GENERATIVE AI TOOLS

Somewhat ironically, I find myself tempted to use AI to write this very statement on the use of AI in this thesis.

I used generative AI tools in the preparation of this thesis to assist with refining and restructuring text, based on original text written by me and source material from the appended papers. The research aim and questions, as well as all results, interpretations, and discussions are entirely my own. All text has been carefully reviewed and verified, and I take full responsibility for the content of this thesis.

During the course of my PhD, AI evolved from being practically nonexistent to becoming part of everyday life. In the early years, when colleagues or friends raised concerns about privacy and AI, my initial reaction was that more urgent challenges, such as climate change, deserved greater attention. Within a relatively short time, however, AI developed into a widely used tool, with implications extending far beyond privacy, encompassing global security concerns, climate impact, environmental sustainability, and questions of justice. Concerns about these broader societal and environmental consequences have led to arguments against its use. At the same time, it is evident that AI tools are becoming an enduring part of society. This raises the need for critical reflection on how we use such tools, and how their use can be made more sustainable.

TABLE OF CONTENTS

LIST OF KEY ABBREVIATIONS

CE	Circular economy
MFA	Material flow analysis
dMFA	Dynamic material flow analysis
GHG	Greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
REE	Rare earth element
HREE	Heavy rare earth element
LREE	Light rare earth element
EoL	End-of-life
c-Si	Crystalline silicon
a-Si	Amorphous silicon
CdTe	Cadmium telluride
CIGS	Copper indium gallium diselenide
PM	Permanent magnet
DD-PMSG	Direct-drive permanent magnet synchronous generators
GB-PMSG	Gearbox permanent magnet synchronous generators
DLS	Decent living standards

CHAPTER 1

Introduction

Energy transitions have historically been closely associated with demands for materials, largely shaping and being shaped by the material foundations of society [1]. The development of energy infrastructure and other provisioning systems, including food production and transport, has expanded global material use from 13 known chemical elements prior to 1750 to more than 100 elements in contemporary society. Until the late 20th century, however, little attention was paid to material use rates, stock accumulation, recycling, and dissipation of materials to the environment [2]. Over the past decades, growing awareness of these dynamics has led to the development of analytical frameworks such as Material Flow Analysis (MFA), which provide critical insights into material requirements, stocks, and losses across socio-technical systems [2].

Low-carbon energy technologies, such as wind turbines and solar panels, are crucial for mitigating human-induced climate change [3]. The consequences of failing to address climate change include more-frequent and more-severe extreme weather events, ecosystem collapse, and profound social and economic disruption worldwide [4]. In response to these threats, nations have come together in a landmark international agreement, the Paris Agreement, which commits signatories to limiting the global temperature rise to well below 2 °C, while pursuing efforts to restrict warming to 1.5 °C above pre-industrial levels by the end of this century [5]. Meeting these temperature targets entails unprecedented reductions in greenhouse gas (GHG) emissions to reach net-zero within an increasingly constrained timeframe, further complicated by a challenging geopolitical context [6]. Owing to delays in implementing deep emission cuts, recent 1.5 °C scenarios indicate that, while limiting warming to 1.5 °C by 2100 remains technically feasible, global temperatures are now projected to temporarily exceed this threshold, very likely within the next decade [6]. Despite the potential roles of low-energy-demand [7] and degrowth [8] scenarios, low-carbon energy technologies will need to be rapidly and substantially expanded to meet climate change mitigation targets at the scale and speed required to meet the Paris Agreement targets.

As fossil fuels are gradually replaced by renewable energy and other low-carbon technologies, the future low-carbon energy system is expected to involve a lower overall level of mining compared with the existing fossil fuel-based system [9]. Furthermore, unlike fossil fuels that are burned and lost permanently, the materials accumulated in low-carbon technologies remain in the urban mine and can be re-circulated, albeit with some unavoidable losses [10,11]. Nonetheless, low-carbon technologies, including wind turbines and solar panels, are material-intensive [12], and are more mineral-intensive [13] than fossil fuels. Consequently, the global demands for the materials required to produce renewable electricity are anticipated to increase significantly [14–17]. As the adoption of wind and solar technologies is expected to continue to grow rapidly to meet global decarbonization goals, understanding the material-related dynamics of this expansion becomes increasingly important.

While the energy transition does not seem to be limited by the geologic availability of minerals [18,19], their supply chains are associated with environmental pressures, including increased land, air, and water pollution [20–23], as well as biodiversity loss [24]. In addition, the supply chains of materials associated with renewable technologies and their infrastructures are associated with GHG emissions [15,25]. Although wind and solar photovoltaic technologies are widely regarded as the cornerstones of an emissions-free electricity system, achieving such a system requires accounting for the emissions generated not only during operation but also throughout the supply chains of the materials upon which they rely. This consideration is especially relevant for structural materials such as steel and concrete, given that concrete production and steelmaking, which supply two of the main structural materials for wind turbines and their foundations, together account for roughly one-eighth of global GHG emissions [26], and are considered hard-to-abate sectors [27,28]. Yet, despite their significance, embodied emissions associated with the growing demand for renewable energy generation technologies remain insufficiently quantified and are frequently overlooked in the literature [15].

In terms of social impacts, the energy transition, as it is currently planned, carries the risk that the increased burden of mineral extraction will be disproportionately placed on low-income or Indigenous communities [29,30], thereby further worsening inequities within and between countries [31]. Overall, a large body of literature shows that supply-side solutions to support the energy transition will exacerbate and intensify social and ecological injustices [30,32,33] and further impede global sustainability goals [34,35]. The substantial impact associated with material supply chains on a planetary scale, driven by the supply-side decarbonization strategies that currently predominate, raises critical research questions for which new analytical tools are required to represent the material dimensions of decarbonization scenarios [31].

Beyond the environmental, climate, and social impacts, the rapid scale-up of low-carbon energy technologies raises fundamental questions regarding the feasibility and equity of the allocations of available metals. Feasibility refers to whether sufficient metals are available and distributed in a way that enables all countries to decarbonize at the speed and scale required to meet the Paris Agreement targets. Equity refers to how available metals should be allocated across countries in order to be in line with the principles embodied in internationally agreed frameworks, including the UNFCCC's concept of Common but Differentiated Responsibilities and Respective Capabilities, as reaffirmed in the Paris Agreement, and in Agenda 2030 for sustainable development. Currently, metals are not allocated through any international framework. Instead, they are governed by national authorities or managed at sub-national or company levels, with access to and demand shaped primarily by market dynamics, geopolitics, and security concerns. Nevertheless, equitable allocation exercises can inform research and policy debates by enabling systematic analyses of how different decarbonization scenarios affect fairness with respect to metal use across countries.

Existing evidence indicates that, in addition to uneven distribution of geological endowments, the material stock in energy systems is unevenly distributed across countries, a trend that is expected to persist. Per-capita metal stocks in electricity infrastructure (power plants, grids and transformers) are substantially higher in industrialized countries and closely linked to income levels [36]. Taken together, China, the European Union (EU), and the United States are estimated to account for around 71% of global in-use rare earth element (REE) stocks in wind turbines and electric vehicles by mid-century [37]. Unequal accumulation of material stocks is also evident beyond the energy sector. An analysis of global steel stocks conducted by Watari and Fishman [38] shows that while most countries in the Global South remain below globally feasible steel stock levels within a Paris-compliant carbon budget, many countries in the Global North have already exceeded these levels. Therefore, they conclude that continued expansion of steel-intensive assets in high-income regions may limit opportunities for infrastructure development in other regions. Although Watari and Fishman [38] do not focus specifically on energy-related steel use, its central insight, that uneven material stock accumulation in some regions may constrain development in others, is directly relevant to metals that are required for the renewable energy technologies. Persisting disparities in metal stock distributions may, thus, hinder the ability of some countries to expand renewable energy systems at a scale and pace that are consistent with their decarbonization and development objectives [38,39].

Despite their relevance, questions as to metal allocations among countries are not yet systematically represented in energy systems models, including the integrated assessment models used by the Intergovernmental Panel on Climate Change (IPCC) to study climate change mitigation scenarios. These models typically constrain technology deployment in relation to cost alone, implicitly assuming an unlimited supply of materials [40].

Incorporating material constraints and allocation considerations is, therefore, an important research and policy priority for understanding the global feasibility and equity implications of rapid and large-scale renewable energy deployment.

In this context, the circular economy (CE) is presented as a possible means to mitigate the climate and material risks associated with the rapid deployment of low-carbon technologies [16,41–45]. CE was theoretically established in the field of industrial ecology in the early 1990s [46], although its core principles are rooted in earlier works, including Rachel Carson's "Silent Spring", which was first published in 1962 [47], and Barry Commoner's "Four Laws of Ecology" [48]. While the concept of a CE has gained prominence only in recent decades, many of its core principles, such as material recycling, repair, and reuse, have long been embedded in societal practices and applied in various forms for centuries.

Despite its potential trade-offs [49,50], CE is increasingly recognized as a promising approach for addressing sustainability challenges linked to the energy transition [51]. In certain sectors, it is considered the 'third pillar' of deep decarbonization, following energy efficiency and low-carbon energy supply [52,53]. However, despite its growing prominence in academic and policy debates, the extent to which CE can effectively mitigate climate and material impacts at the scale required for the energy transition remain uncertain.

Against this background, there is a need for integrated analyses that systematically assess how CE strategies influence material demand and supply requirements, their associated climate impacts, and the equity implications of material allocation across countries. The overall aim and the associated research questions developed in this thesis are presented in Section 1.1.

1.1 Aim and research questions

Building on the gaps identified above, the overall aim of the thesis is to examine how CE strategies can reduce embodied emissions, decrease material demand and supply requirements, and support more equitable material allocation in renewable electricity generation technologies during the energy transition.

CE strategies in this thesis refer to the following four strategies: longer service lifespan, material intensity reduction, substitution, and recycling. Longer service lifespan extends the service life of technologies through improved technology design, thereby reducing the frequency of replacements. Material intensity reduction involves decreasing the material content per unit of installed capacity through increased metal efficiency or optimized product design. Substitution refers to the replacement of materials in final applications with alternative materials, components, or technologies. Recycling involves recovering materials from decommissioned technologies to create secondary raw materials.

This thesis encompasses both structural and technology-specific materials. Structural materials are bulk materials that provide the physical support and mechanical strength of a structure. Technology-specific materials are materials that enable the specific function or performance of a technology. They are typically used in smaller quantities but are essential for how the technology operates.

A clear understanding of the aim requires further definition of the following terms: embodied emissions, material demand, material supply requirements, equitable material allocation, renewable energy generation technologies, and energy transition. These terms are defined within the scope of this thesis in Chapter 2, *Background*.

This aim is addressed through the following research questions (RQs), which are operationalized through the definitions and scope outlined here and in the *Background* chapter.

RQ1: *To what extent can CE strategies reduce the embodied emissions associated with structural materials for wind turbines and their foundations during the energy transition?*

RQ2: *How do individual CE strategies affect the demand for materials and the supply requirements for wind and solar technologies, how do their effects compare in terms of magnitude and timing, and what combined effects and trade-offs arise from their joint implementation during the energy transition?*

RQ3: *To what extent is the required material supply for wind power during the energy transition compatible with selected equity principles, and how can CE strategies improve this compatibility?*

Sweden and the EU serve as the geographical case studies in this thesis. The appended articles vary in their geographic focus, with some examining Sweden and others the EU. While the overall aim encompasses both wind and solar power technologies, not all articles address both; some focus exclusively on wind power, while others include both wind and solar. In terms of materials, all articles consider technology-specific materials, whereas only one includes structural materials. Consequently, not all research questions are addressed across all case studies, technologies, and material categories. These distinctions are specified in the scope of each appended article and summarized in Section 1.2.

1.2 Scope and contribution of the research

This thesis comprises four appended articles, which together examine the effects of CE strategies on embodied emissions, material demands, material supply requirements, and equitable material allocation, thereby highlighting why *matter matters* in the transition to a low-carbon energy system. The CE strategies, effect areas, geographies, technologies, and materials covered in the appended articles are illustrated in Figure 1.1.

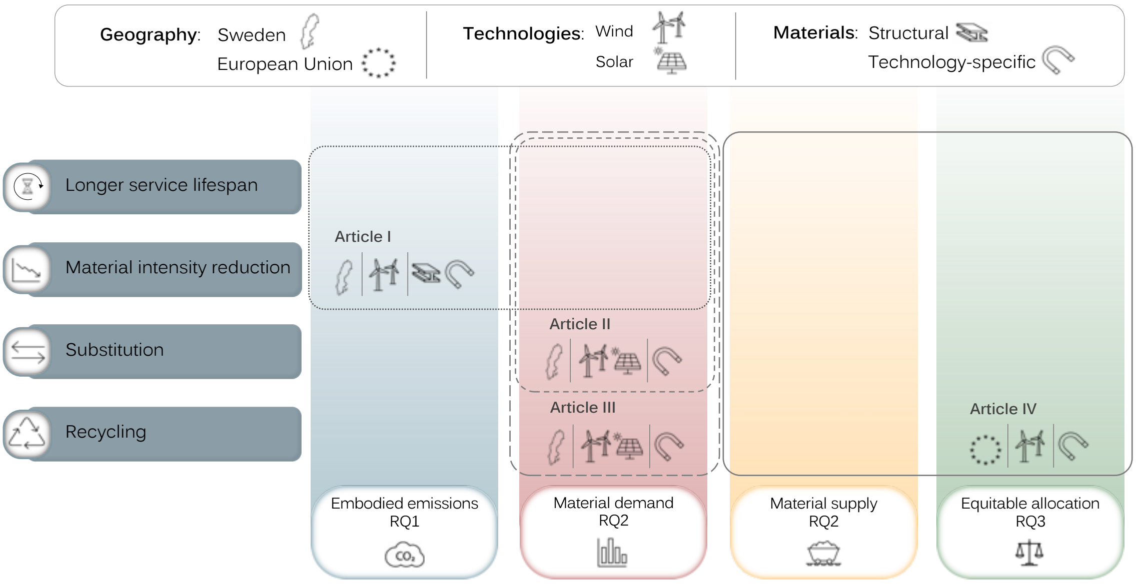

Figure 1.1: Illustration of how the four appended articles collectively examine CE strategies and their effects on embodied emissions, material demand, material supply, and equitable material allocation. The geography (Sweden and European Union), technology (wind and solar power) and material (structural and technology-specific) coverages of each article are also indicated. Source: Author's own illustration; visual layout adapted from Verena [54].

Article I develops a modelling methodology to analyse the material flows in wind energy systems. It examines the material requirements for wind power deployment under multiple electricity decarbonization scenarios that represent different technology deployment pathways. It assesses the potential availability of secondary materials from wind turbines and their foundations during the energy transition, and it quantifies the associated embodied emissions. The analysis focuses on two structural materials, concrete and steel, used across all wind technologies and their foundations, as well as two REEs, neodymium and dysprosium, used in permanent magnets (PM) of wind turbines' generators. The results for the structural material flows provide the basis for estimating embodied carbon emissions up to 2050 under alternative assumptions related to emissions control and industrial development roadmaps. Sweden is used as a case study. Although not explicitly framed as such in **Article I**, the methodology incorporates two CE strategies, longer design lifespan and material intensity reduction, and identifies trade-offs that arise from their combined implementation. Overall, **Article I** directly contributes to *RQ1* and *RQ2* of the thesis and establishes the methodological foundation upon which **Articles II–IV** build.

Article II builds on the methodology introduced in **Article I** to investigate the effects of individual CE strategies related to technology design improvements on the future demands for technology-specific materials and assesses their potentials to contribute to closing the metal loops during the energy transition. The CE strategies included are: longer design lifespan, material intensity reduction, and substitution with novel technologies. The technology scope is expanded to include solar power in addition to wind power, and the analysis focuses on eleven technology-specific metals, with Sweden as a case study. This analysis is conducted using a single input scenario that is characterized by the rapid deployment of wind and solar technologies up to 2050, consistent with climate mitigation targets. Overall, the work conducted in **Article II** contributes to *RQ2* of the thesis.

Article III further expands the scope of CE strategies by incorporating recycling, thereby adding an end-of-life (EoL) strategy, in addition to the three CE strategies that are implemented at the technology design stage. The technology scope remains focused on wind and solar technologies, although the material scope is narrowed to a subset of the metals analysed in **Article II**, specifically those listed as both critical and strategic raw materials under the European Commission's 2024 Critical Raw Materials Act. Sweden is again used as a case study. The article evaluates how CE strategies influence material flows and assesses their potential to contribute to closing the metal loops, while also examining whether trade-offs arise from their combined implementation. In addition, the metal demand is assessed relative to an equal-per-capita share of primary production, to assess the current capacities of the extraction and refining industries to supply the metals under study. The analysis uses the same single input scenario as **Article II**, characterized by the rapid deployment of wind and solar technologies up to 2050. Overall, the work conducted in **Article III** contributes to *RQ2* of the thesis.

Article IV brings together insights from the fields of industrial ecology and climate justice to develop a framework for assessing material allocations under an equity lens, based on three equity principles: equality, need, and capability. It further examines the extents to which CE strategies improve compatibility with these principles. The analysis is confined to wind power technologies and focuses on four technology-specific metals: neodymium, praseodymium, dysprosium, and terbium, all of which are REEs. The article applies the same set of four CE strategies as in **Article III**: longer design lifespan, material intensity reduction, substitution, and recycling. Using the EU as a case study, the analysis is conducted under a single input scenario that reflects EU Member States' wind power deployment plans. Overall, **Article IV** assesses whether the EU's wind power plans entail a disproportionate claim on the supply of REEs when evaluated against the three equity principles. The work described in **Article IV** contributes to *RQ2* and *RQ3* of the thesis.

1.3 Thesis structure

This thesis consists of this introductory essay and the four appended articles. This introductory essay is structured into eight chapters that synthesize the main findings of the appended articles and position the research within its broader scientific and policy contexts.

Following this introductory chapter, which outlines the background, motivation, and scope of the thesis, Chapter 2 provides an overview of the key concepts and distinctions that are needed to contextualise the research aim and to understand the literature landscape and research gap addressed in Chapter 3. Chapter 4 introduces the main methodological concepts and approaches applied and presents an overview of the modelling framework and scenarios developed.

The main findings of the thesis, including the supplementary analyses conducted to support the research questions posed, are presented and discussed in three thematic chapters. Chapter 5 focuses on embodied emissions, Chapter 6 on material demands and supply, and Chapter 7 on equitable material allocation.

Chapter 8 discusses the generalizability of the results, reflects on their relevance for stakeholders in policy, industry, and research, examines the study's limitations, and outlines directions for future research.

Conclusions are drawn in Chapter 9.

CHAPTER 2

Background

What concepts, distinctions, and elements of existing knowledge are required to understand the thesis aim and its contribution to the literature? This chapter addresses this question by defining the main concepts in the research aim and establishing the conceptual foundations underpinning the analyses presented in this thesis. It introduces key frameworks and definitions related to CE strategies, the energy transition, embodied emissions, material demand and supply chains, and equity-based material allocation.

Together, these concepts provide a common analytical language that contextualizes the research aim defined in Chapter 1, informs the review of related work in Chapter 3, underpins the methodological choices described in Chapter 4, and supports the interpretation of the results presented in Chapters 5–7.

2.1 Circular economy strategies

CE strategies can be categorized in different ways (Figure 2.1). In 2016, Bocken et al. [55] introduced the *Slow–Narrow–Close* framework of material flows for strategies to move from a linear form to a CE. *Slow*, as the name suggests, is about slowing down the flow of resources through the prolonged use and reuse of products over time. This can be achieved through the design of long-lasting products and strategies for product lifespan extension (for instance, through repair and remanufacturing). *Narrow* refers to reducing resource use per unit of product. *Close* refers to the closing of the resource loop between the EoL and production stages of a product's lifecycle, thereby creating a circular flow of resources. This is achieved through recycling.

This framework can be expanded by integrating the technology lifecycle as a category to classify CE strategies [56]. In particular, CE strategies can be categorized along the technology lifecycle, differentiating strategies that can be implemented during the technology design and the manufacturing, operation and maintenance phases, as well as the EoL management phase.

These categorizations provide the conceptual basis for selecting and interpreting CE strategies in the results presented in Chapters 5–7.

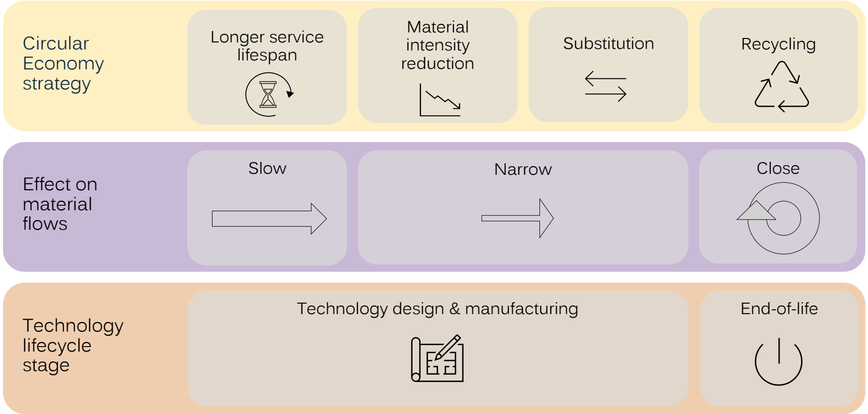

Figure 2.1: CE strategies included in the introductory essay of this thesis, organized according to their effects on material flows based on the Slow–Narrow–Close framework, and their stages throughout the wind and solar technology lifecycle (from technology design and manufacturing to operation and maintenance, to EoL). Source: Author.

2.2 Energy transition

The energy transition is defined as the transition towards a low-carbon society that is consistent with the climate change mitigation targets of the Paris Agreement. This definition of the energy transition encompasses not only the large-scale deployment of renewable technologies to reduce GHG emissions, but also a temporal dimension that requires emissions to decline sufficiently rapidly to limit global warming to well below 2 °C above pre-industrial levels, while pursuing efforts to limit warming to 1.5 °C by 2100. In line with these objectives, the EU and Sweden, which serve as the geographical case studies in this thesis, have set targets to achieve net-zero GHG emissions by 2050 and 2045, respectively.

Decarbonization scenarios have been developed to map how these climate mitigation targets could be achieved, illustrating, among other aspects, the deployment of renewable electricity generation technologies at national, regional and global levels. These scenarios are typically produced using a range of energy systems models that differ in methodology and purpose, including optimization-based and simulation-based approaches. Some models are designed to explore specific technical questions, while others are developed to inform policy-making. Most focus primarily on supply-side transformations, although a growing body of work increasingly incorporates demand-side measures and behavioural aspects of decarbonization [57]. However, many of these scenarios, including the integrated assessment model scenarios used in the IPCC, often disregard material aspects of the energy transition [40].

2.2.1 Renewable energy generation technologies

By renewable energy generation technologies, this thesis refers to wind turbines and solar panels. For wind turbines it covers both onshore and offshore wind power systems. Wind turbines can be broadly categorized into two main configurations: direct-drive and gearbox. Within each configuration, several sub-technologies exist. Some of these sub-technologies employ REEs in their PM, occurring under both configurations, albeit with different material intensities [58]. **Articles I–IV** focus on these two main sub-technologies. In addition, **Article I** includes all remaining wind turbine sub-technologies, so as to provide a complete representation of the steel and concrete requirements for wind turbine and their foundations. For solar power, distributed and centralized grid-connected applications are considered, while off-grid solar capacity is excluded. **Articles II** and **III** cover the commercially available solar power technologies, from both first-generation and second-generation technologies. Four sub-technologies are considered: wafer-based crystalline silicon (c-Si), amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium diselenide (CIGS). Table 2.1 shows the technology scope of the thesis.

2.3 Embodied emissions

Embodied emissions are defined as the emissions that are associated with the structural materials, specifically steel and concrete, used in wind power.

Steel is used mainly in the structural elements of wind turbines, such as the tower and core mechanical structures. Steel is also used in the reinforcing and anchoring components of the foundations of both onshore and offshore wind turbines. Concrete is primarily used in the wind turbine foundations of both onshore and offshore wind turbines.

The quantitative assessment of these structural materials is motivated by the GHG emissions associated with their supply chains. Globally, the steel and concrete industries together account for approximately one-eighth of total GHG emissions [26]. Steel production and cement production (which is required for concrete), are widely considered hard-to-abate sectors due to their reliance on carbon-intensive processes and limited availability of mature, low-carbon alternatives [27,28]. In the absence of effective mitigation measures in material processing industries, the emissions associated with structural materials, primarily steel, across all end-use sectors can account for up to 10% of the remaining global carbon budget, corresponding to a 50% probability of limiting global warming to 1.5 °C [15]. Therefore, demand-side mitigation measures are particularly relevant.

The geographic focus of the embodied emissions analysis is Sweden. Sweden is a highly industrialized economy, in which energy- and emissions-intensive industries, particularly steel and cement production, play central roles. These sectors constitute key components of the national manufacturing base and position Sweden among the major producers of steel and cement in the EU. As a consequence, the cement and steel industries together account for approximately 15% of Sweden's national GHG emissions, with the cement industry contributing about 4% and the steel industry more than 10% [59,60]. In support of Sweden's target to achieve net-zero GHG emissions by 2045, sector-specific roadmaps for the decarbonization of the steel and cement industries have been developed [59,60].

Emissions associated with these industries occur throughout the supply chains of the materials and include extraction, transportation, and production stages. At present, the emissions from extraction and transportation are negligible compared with the emissions generated during production [61]. Production-related emissions arise primarily from the underlying chemical processes. In steel production, emissions are mainly associated with the blast furnace processes used to reduce iron from iron ore [61]. In cement production, the emissions largely originate from clinker production, which relies on fossil fuels and involves process emissions from limestone calcination [61]. Although Swedish and European industries are investing in the decarbonization of both steelmaking and cement production, this transition will require time and the large-scale deployment of emerging technologies. These technologies include hydrogen-based direct reduction in steelmaking and the use of alternative fuels derived from waste and biomass, combined with carbon capture and storage, in the cement industry.

2.4 Material demand and supply

2.4.1 Material coverage

Material demand in this thesis encompasses both structural and technology-specific materials. Structural materials include steel and concrete. Technology-specific materials include eleven metals: four REEs (neodymium, praseodymium, dysprosium, and terbium) that are used in wind power; and seven minor metals that are used in solar power (silver, germanium, cadmium, tellurium, indium, gallium, and selenium).

REEs represent a group of seventeen metallic elements that share similar chemical properties. While they are not truly rare in the Earth's crust, they are seldom found in economically viable concentrated deposits [62]. REEs are of particular importance for the energy transition, as several elements, especially neodymium, praseodymium, dysprosium, and terbium, are key components of PM used in wind turbine generators and electric vehicle traction motors. REEs are commonly categorised into light rare earth elements (LREEs) and heavy rare earth elements (HREEs) based on their atomic number and associated chemical-physical properties. Neodymium and praseodymium are LREEs, while dysprosium and terbium are HREEs.

Minor metals are metallic elements produced in relatively small quantities, often as by-products of major metal mining and refining rather than from dedicated primary ores. They are typically not traded on major commodity exchanges and are critical to specialised high-technology applications, including renewable energy systems, electronics, and advanced alloys [63]. In some industrial, economic, and policy contexts, REEs are also classified as minor metals due to their relatively low production volumes, limited number of producers, and heightened supply risk [64]. Table 2.1 shows the materials included in each sub-technology.

Table 2.1: Technology, sub-technology, component, and material layers of wind and solar technologies included in the thesis. The inclusion of technologies, sub-technologies, components and materials in **Articles I–IV** is denoted. Source: Adapted from **Article III**.

Technology	**Onshore and offshore wind turbines** (**Articles I–IV**)	**Distributed & centralized grid-connected solar panels** (**Articles II** and **III**)
Sub-technology	Direct-drive permanent magnet synchronous generators (DD-PMSG) Gearbox permanent magnet synchronous generators (GB-PMSG) (**Articles I–IV**)	Crystalline silicon (c-Si) Amorphous silicon (a-Si) Cadmium telluride (CdTe) Copper indium gallium diselenide (CIGS) (**Article II**)
	Remaining sub-technologies (**Article I**)	Amorphous silicon (a-Si) Copper indium gallium diselenide (CIGS) (**Article III**)
Component	REE-containing permanent magnets	Solar cells
Material	Concrete (wind turbine foundations) Steel (wind turbines and foundations) Neodymium (DD-PMSG & GB-PMSG) Dysprosium (DD-PMSG & GB-PMSG) (**Article I**)	Silver (c-Si) Germanium (a-Si) Cadmium, Tellurium (CdTe) Indium, Gallium, Selenium (CIGS) (**Article II**)
	Neodymium (DD-PMSG & GB-PMSG) Praseodymium (DD-PMSG & GB-PMSG) Dysprosium (DD-PMSG & GB-PMSG) Terbium (DD-PMSG & GB-PMSG) (**Articles II–IV**)	Germanium (a-Si) Gallium (CIGS) (**Article III**)

2.4.2 Gross and primary material demand

Material demand can be expressed as gross or primary demand. Gross demand refers to the total requirement for a material and can be satisfied through primary supply, derived from new extraction and processing, and secondary supply, obtained from recycling and other non-primary sources.

In an ideal case, all gross demand would be met by secondary supply, thereby closing resource loops and eliminating the need for primary supply, which is generally associated with higher supply-chain environmental impacts [65–70]. However, during the energy transition as currently planned, rapidly increasing demand for renewable electricity necessitates continued expansion of primary supply. In addition, most metals considered in this thesis currently have negligible recycling rates [71] (see Table S1.1 in Supplementary material of **Article II**). Consequently, reducing gross demand at present largely corresponds to reducing primary demand.

This relationship may evolve as recycling efforts expand, in line with the European Commission's target to meet 25% of the EU's strategic material demand through recycling by 2030 [72]. While reducing the gross demand is expected to remain important, especially given the scale and speed required to decarbonize the energy system, increasing the contribution of the secondary supply is widely regarded as a key CE strategy for closing material loops and reducing reliance on primary extraction.

2.4.3 Material supply requirements

Metal availability indicators

Three data sources are commonly used for indicating metal availability: *production*, *reserves*, and *resources*. Each carries distinct advantages and limitations in relation to expressing metal availability, and all three evolve in response to market conditions, technological developments, and geopolitical factors. For the purposes of this thesis production and reserves are used.

Production represents the industry's current capacity to supply metals. It is often expressed as the amount of metal per year. It provides a useful short-term benchmark for metal availability, although it is strongly correlated with demand: for metals with rapidly increasing demands, such as those required for renewable energy technologies, the current production levels are likely to increase over time. Using today's production as a static benchmark may, therefore, may underestimate future availability. For longer scenario periods, dynamic production values that incorporate expected growth rates could offer a more-appropriate reference.

Reserves reflect the portion of known deposits that can be economically extractable under present conditions. Global reserves tend to be more stable over time, as ongoing exploration and improved geological knowledge often offset the depletion of extracted materials [73]. For some metals, their reserves have grown substantially in recent years in response to rising demand and expanded exploration efforts. Reserve estimates remain sensitive to economic conditions and reporting practices.

Losses along the metal supply chains

During the metal cycle, from metal production through fabrication and manufacturing, use, and EoL management, losses occur at each stage [74]. This thesis focuses on the losses that occur during metal production, fabrication and manufacturing, and EoL management. These losses are represented through stage-specific yield and recovery rates, which are defined as follows.

Production yield rate refers to the share of metal remaining after the successive crushing, concentrating, smelting, and refining processes through which ores are transformed into refined metal flows with varying degrees of purity.

Fabrication and manufacturing yield rate encompasses all the steps required to transform refined metal flows into final products, accounting for material losses during component manufacturing and assembly.

Old scrap collection rate (hereinafter referred to as the collection rate) reflects the quantity of the EoL metal contained in decommissioned technologies that is collected and enters the recycling chain.

Recycling process efficiency rate (hereinafter referred to as the recycling rate) is the efficiency of any given recycling process, also referred to as the recycling yield or recovery rate. Metals are considered to be retained during functional recycling, which is the process whereby metals from decommissioned technologies are separated, sorted, and processed to produce recycled metals that are returned to raw metal production.

The process of recovering the same metal from different technologies may necessitate distinct methodologies. The individual technology design, the form in which the metal is used, and its combination with other materials can greatly affect the specificity and complexity of the recovery process. Therefore, for the collection of data, the recycling process efficiency rate of the metals associated with specific technologies is important.

Overall, in this thesis, material supply requirements refer to two components: required annual metal production and required metal reserves. Required metal production denotes the annual level of metal production needed to support the deployment of renewable energy generation technologies under the decarbonization scenarios considered. Required metal reserves refer to the cumulative amount of metal that must be available over the assessed transition period to enable this deployment. These supply requirements account for the reductions in metal demands resulting from the implementation of CE strategies, including the losses along production, fabrication and manufacturing, and EoL management. For recycling, secondary materials are assumed to substitute for primary material demand.

These considerations inform the assessment of the compatibility of required supply with equity-based allocation presented in Chapter 7, *Equitable allocation*.

2.5 Equitable material allocation

In this thesis, equitable material allocation refers to the allocation of materials across countries according to selected equity principles.

2.5.1 Equity principles

Distributive justice as a concept in moral and political philosophy has a long history [75]. It addresses how welfare, goods, opportunities, and freedoms should be distributed among individuals or groups in order to account for fairness. At its core, distributive justice is concerned with outcomes, that is, “who gets what” [76]. These outcomes are typically assessed according to normative principles.

Research and policy studies are increasingly concerned with issues of justice and equity in the context of climate change. Calls for climate justice are based on the recognition that climate change affects people differently, unevenly, and disproportionately, such that the resulting injustices need to be addressed in fair and equitable ways [77].

Within this broader climate justice framework, distributive justice has become particularly relevant for climate mitigation. Equity principles have increasingly been applied to quantify each country's fair share of the remaining carbon budget [78]. Widely applied principles, partly because they align with the UNFCCC’s principle of Common but Differentiated Responsibilities and Respective Capabilities, include responsibility, capability, need, and equality [78–81]. **Responsibility** refers to the degree to which a country or population has so far contributed to climate change and connects that to the obligation to address that change. **Capability** refers to a country's economic ability to contribute to addressing climate change; broadly speaking, this is the share of its financial resources that can reasonably be mobilized, taking into account domestic development needs. The **need** principle, sometimes called the right to development, holds that people have different resource needs depending on their location, climate, and economic and development situations. **Equality** holds that every human being has equal worth. In the literature there are multiple interpretations of this principle [78]. The most-common interpretation is that every individual has an equal right to available resources. Another interpretation holds that those in equal positions are required to contribute equally to addressing climate change [78,82].

This work extends the application equity principles from the carbon budget to metal availability. Recognizing that other equity principles exist, including ones that are more difficult to quantify, and which carry their own ethical weight [78], this thesis focuses on three of the four core categories that have received systematic treatment in the literature: equality, need, and capability. Allocating metals for low-carbon technologies is different conceptually to allocating carbon budgets, which suggests that the equitable allocation of metals deserves a dedicated approach. Sections 2.5.2–2.5.5 elaborate on some of these conceptual differences.

2.5.2 Governance of metals

Earth system components such as the atmosphere, the ozone layer, and the biosphere are widely recognized as global commons. The atmosphere’s status as a global common underpins the international governance of emissions through multilateral frameworks developed under the UNFCCC, including the Paris Agreement. These frameworks establish collective goals, such as global temperature limits, provide normative principles, including Common but Differentiated Responsibilities and Respective Capabilities, and enable international coordination, reporting, and review.

In contrast, despite their central role in addressing climate change, energy transition metals, defined as metals that are essential for the deployment of low-carbon energy technologies, are not governed under comparable international frameworks and are rarely treated as part of a global commons problem. Metals are typically governed by national authorities or managed at sub-national or company levels. This governance structure is reinforced by United Nations General Assembly Resolution 1803 (XVII) of 1962, which affirms States' permanent sovereignty over natural resources within their territories. At the same time, metal reserves are geographically unevenly distributed across regions, as is the case for REEs, with significant implications for access and supply security [37,83,84]. In practice, access to and demand for primary metals are shaped primarily by market dynamics, geopolitics, and security considerations.

However, given that energy transition metals are finite and essential inputs for low-carbon technologies, sufficient quantities must become available and be distributed in a manner that enables all countries to decarbonize at the speed and scale required to meet the targets of the Paris Agreement. From this perspective, the concept of the commons can be extended to metal resources, particularly when these resources are understood as enabling solutions to the shared global challenges related to climate change and development [39,85].

2.5.3 Metal budget

For a specified temperature target, such as limiting warming to 1.5 °C or 2 °C, the associated carbon budget represents the total carbon emissions that can be released while still keeping global temperatures below that threshold [6]. Carbon budgets are thus grounded in science-based limits linked to climate stabilization. The target for climate stabilization is, in turn, defined by the Paris Agreement, an international treaty that commits signatories to limiting the rise in global temperature to well below 2 °C above pre-industrial levels by the end of this century.

For metals, however, no comparable global agreement exists. This absence reflects the governance structure for metals, as described in Section 2.5.2. It may also reflect the relatively recent understanding of the extent of the material increases required for the energy transition. It also reflects the heterogeneous nature of metals, which differ in physical characteristics, end uses, extraction pathways, environmental and climate impacts, and geographic distribution. As a result, no single aggregated metric can capture these differences, and each metal would require its own benchmark.

In this thesis, metal availability is used as an indicator of a metal budget. At the same time, this approach acknowledges that it represents only one possible indicator. Alternative, potentially more comprehensive metrics could account for other important aspects, such as the need to reduce carbon emissions but also for broader environmental and social considerations, such as biodiversity loss and human rights.

2.5.4 Methodological choices and uncertainty

The dynamic nature of global metal production and reserves means that using them as indicators of future availability requires assumptions that are specific to each metal and how it may change over time. The suitability of these assumptions depends on the time horizon considered, since uncertainty increases as projections extend further into the future. In some cases, dynamic benchmarks are justified and have been applied in the literature, particularly for annual production levels [37,39]. However, adopting such dynamic approaches entails assuming future growth or decline rates, which in turn shape estimates of availability.

These uncertainties also influence how allocation results should be interpreted. Given the variability and ongoing debate surrounding availability estimates, and the fact that allocation frameworks ultimately support forward-looking decisions, the resulting figures should be viewed as indicative of orders of magnitude rather than precise thresholds. Accordingly, the purpose of metal allocation analysis is not to define exact allowable quantities, but to evaluate whether projected demand is broadly compatible with plausible ranges of physical availability.

2.5.5 Technology-specific versus economy-wide allocation

In carbon budget allocations, principles are typically applied at the national level, leaving countries to select mitigation strategies that can be tailored to their specific circumstances. When considering metals, however, it is worth questioning whether allocation could be defined at the level of individual technologies, since national technology portfolios differ depending on factors such as renewable resource availability and electrification needs, leading to substantial variation in future material demand across countries.

Nevertheless, wind and solar power are included in all national decarbonization strategies and have expanded rapidly across a wide range of contexts, as evidenced by countries' first Biennial Transparency Reports [86]. Their widespread role in climate mitigation supports assessing metal allocation at the level of specific technologies.

An additional consideration is that many metals have multiple uses across different sectors, both within and beyond low-carbon technologies. REEs, for instance, are employed in applications ranging from wind turbine generators and electric vehicles to electronics, medical devices, and increasingly military technologies. As a result, focusing on a single technology captures only a portion of overall demand and may underestimate pressures on material availability.

CHAPTER 3

Related work

The requirements for materials associated with low-carbon energy technologies across energy transition pathways have been extensively examined at the global scale , and to a lesser extent at the European [22,87–90] and national levels [16,41,91–93]. These previous studies have explored the material demand implications for low-carbon technologies, under different decarbonization scenarios, varying with respect to geographic scope, temporal resolution, technological detail, and material coverage. Collectively, this body of the literature has established that rapid deployment of low-carbon technologies, including renewable electricity generation technologies, is associated with substantial increases in the demand for a range of metals and structural materials.

3.1 Embodied emissions

Within this broader body of work, despite renewable electricity generation technologies being central to pathways that aim to achieve an emissions-free electricity system, the emissions embodied in the production and processing of materials required for these technologies and their associated infrastructure remain insufficiently addressed in the literature [15]. This is particularly the case for structural materials, such as the steel used in wind turbine towers, foundations, and other components, and the concrete used in turbine foundations. As a result, the embodied emissions associated with renewable energy deployment, and the effects of CE strategies in reducing embodied emissions are frequently underestimated or omitted altogether (Table 3.1).

3.2 Material demand

Beyond embodied emissions, within this broader body of work, a subset of studies has incorporated CE strategies related to wind and/or solar technologies into assessments of material requirements for low-carbon energy transitions (see Table 3.1). Existing scenario-based analyses that include CE strategies have focused mainly on recycling as the central mechanism for reducing the demand for primary materials. In contrast, technology design-stage CE strategies, such as material intensity reduction, substitution of materials or technologies, and the extension of technology service lifespans, have received considerably less attention (Table 3.1).

Among these design-stage strategies, substitution is particularly underexplored. When considered, substitution has mostly been limited to commercially mature technologies. However, recent industrial announcements signal increasing interest in novel substitution pathways, which involve high-temperature superconducting technologies and ferrite-based PM for wind power, as well as perovskite solar cells and silver-free c-Si photovoltaics for solar power [94–97]. As these technologies progress towards commercialization, their implications for demands for materials warrant a systematic assessment, notwithstanding potential technical and environmental trade-offs.

The extension of service lifespans through improved technological design has likewise received limited attention in the literature, despite its potential relevance, especially for onshore wind power systems, which expanded rapidly from the early 2000s in many countries. While wind power plants with guaranteed 30-year service lifespan are already being commissioned (S. Fogelström, Swedish Wind Centre, personal communication, May 3, 2023), most scenario studies continue to assume lifespans of 25 years or shorter throughout the modelling horizon [13,15,16,18,45,98–104]. Given that a substantial share of existing wind capacity is expected to reach EoF in the coming years, assessing the implications of longer service lifespan for future material demands becomes increasingly important.

With the exception of Li and Adachi [43], who examined a single solar sub-technology (crystalline-silicon) and one metal (silver) and focused on material intensity reduction, no study to date has systematically assessed the combined effects of multiple CE strategies, namely longer service lifespan, material intensity reduction, substitution, and recycling, on the material demands for renewable energy technologies (Table 3.1). Furthermore, while Li and Adachi [43] included all four strategies, their analysis does not provide a comparative assessment of the relative effectiveness and interactions.

Collectively, these four strategies span the full spectrum of the Slow–Narrow–Close framework in terms of their effects on material flows. Although previous research has shown that each strategy can individually reduce the material demand, their combined effects, potential synergies, and trade-offs remain largely unexplored.

In addition, studies that have incorporated CE strategies differ in terms of their treatment of material demand metrics. Some have focused on the primary demand, others on the gross demand, while relatively few have considered both simultaneously (Table 3.1). To date, no study has analysed the dynamic interactions between the gross and primary demands following the implementation of CE strategies that span the Slow–Narrow–Close framework.

3.3 Equitable material allocation

Only a few studies have examined the metal allocations in low-carbon transition pathways. These studies vary in their framing: some explicitly adopt an equity perspective, while others use allocation as an indicator of supply feasibility. For example, Lallana et al. [41] have analysed Spain's cobalt and lithium demands relative to equal-per-capita shares of global reserves, explicitly framing their results in terms of equity. In contrast, Morfeldt et al. [105] have used an equal-per-capita benchmark to assess availability rather than equity considerations *per se*. Across these studies, allocation is consistently based on the equality principle, leaving other equity principles largely unexplored. Malmaeus et al. [39] have broadened the allocation framework to include additional approaches compatible with grandfathering and need-based allocation, although they rely on a static population and GDP assumptions, omit supply-chain losses, and do not incorporate CE strategies.

Taken together, existing research constitutes a small but growing body of work on the materials and equity dimensions of low-carbon energy transitions. However, significant gaps in the knowledge remain. No study has simultaneously assessed the metal allocation using a comprehensive set of equity principles while accounting for supply-chain losses, the temporal dynamics across the full scenario period, and the potential influences of CE strategies. More broadly, the compatibility of national and regional decarbonization pathways with equitable access to available metals remains poorly understood.

The aim and research questions (see *RQs 1–3* above) of this thesis are explicitly informed by these gaps in the literature. By integrating the full set of Slow–Narrow–Close CE strategies, modelling material flows and embodied emissions over time, and evaluating metal supply requirements through multiple equity principles, this thesis seeks to advance our understanding of the material, climate and justice implications of the energy transition.

Table 3.1: Dynamic material flow studies in the literature that have evaluated the prospective demands for materials from low-carbon technologies, including circular economy strategies. Several of the studies include other technologies in addition to wind and solar. Source: **Article II**, with additional analysis.

Includes wind and/or solar	Scenario final year	Circular economy strategies included	Embodied emissions studied	Demand(s)	Study
Wind	2050	Recycling, material intensity reduction, substitution, reuse	No	Gross & Primary	[89]
Wind	2040	Recycling	No	Gross	[72]
Wind	2050	Material intensity reduction, longer service lifespan	No	Gross	[83]
Wind	2050	Material intensity reduction	No	Gross	[90]
Wind	2100	Recycling	No	Gross	[91]
Solar	2050	Material intensity reduction, substitution	No	Gross	[96]
Solar	2050	Material intensity reduction	No	Gross	[97]
Solar	2050	Recycling, material intensity reduction, longer service lifespan, substitution	No	Primary	[39]
Solar	2070	Recycling, material intensity reduction	No	Gross	[16]
Wind & solar	2050	Recycling, material intensity reduction, longer service lifespan	Yes	Gross & Primary	[37]
Wind & solar	2050	Recycling, material intensity reduction, substitution	No	Primary	[13]
Wind & solar	2050	Recycling	Yes	Gross	[15]
Wind & solar	2050	MI reduction, longer service lifespan	No	Gross	[84]
Wind & solar	2050	Recycling, material intensity reduction, longer service lifespan	No	Gross & Primary	[98]
Wind & solar	2060	Recycling, material intensity reduction	No	Gross	[10]
Wind & solar	2060	Recycling, material intensity reduction, substitution	No	Gross & Primary	[41]
Wind & solar	2050	Recycling	No	Primary	[99]
Wind & solar	2050	Recycling	No	Primary	[92]
Wind & solar	2100	Recycling, material intensity reduction, longer service lifespan	No	Primary	[79]
Wind & solar	2050	Recycling	No	Primary	[93]
Wind & solar	2050	Recycling, longer service lifespan	No	Primary	[75]
Wind & solar	2040	Recycling, material intensity reduction	No	Primary	[94]
Wind & solar	2050	Material intensity reduction	Yes	Gross	[12]

CHAPTER 4

Methodology

This chapter provides an overview of the methodology used in this work, which is centered on dynamic Material Flow Analysis (dMFA), which is a key method adopted from the field of *industrial ecology*. The dMFA is combined with scenario development based on CE strategies, as applied in **Articles I–IV**. **Article IV** blends together insights from the fields of *climate justice* and *industrial ecology* through the operationalization of equity principles for metal allocation.

This chapter is structured around three core methodological components: material flow systems, scenario development, and equitable metal allocation. For each component, the underlying concepts and definitions are first introduced in a **Conceptual basis** section (Sections 4.1.1, 4.2.1, and 4.3.1). Subsequently, the corresponding **Modelling approach** sections (Sections 4.1.2, 4.2.2, and 4.3.2) describe how these concepts are operationalized and implemented within the modelling framework of this thesis.

4.1 Material flow systems

4.1.1 Conceptual basis

In analogy to the biological processes that make up metabolism, which involve the flow of materials and energy through the human body, materials and energy flow through industrial systems. These flows involve the extraction of raw materials, their transformation into products through various industrial processes, and the management of the waste[1] that is generated during these processes. These flows of resources into and from a particular

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[1] In a fully circular system, the notion of waste does not exist, since materials at the end of their useful life for one process become inputs to the same or other processes. However, in our current industrial systems, since materials and/or products often end up in landfills or incinerators following their useful life, they constitute waste.

industrial system, known in the industrial ecology field as *industrial metabolism*, can be mapped and quantified using a Material Flow Analysis (MFA).

Understanding the MFA methodology requires familiarity with several key concepts, including *processes*, *stocks*, *flows*, and *systems* [106]. In addition, MFAs can be classified based on their *system boundaries* as *static* or *dynamic*, and as *retrospective* or *prospective*. A further distinction relates to the analytical aim of the study, commonly described as *inflow-driven* or *stock-driven* MFA. The following paragraphs define these concepts, followed by an overall definition of MFA.

A *process* is defined as the transportation, transformation or storage of materials [106]. All three processes can occur naturally or may be the result of human activity. Examples of natural processes include: the movement of dissolved lithium in groundwater (transportation); photosynthesis, whereby plants convert carbon dioxide and water into glucose and oxygen using sunlight (transformation); and natural sequestration of carbon dioxide in marine sediments (storage). Examples of human-made processes include municipal waste collection (transportation); the production of plastics from crude oil (transformation); and the stockpiling of REEs in strategic reserves (storage). In MFA studies, the processes can cover a part of, or the entirety of, the lifecycle of a material [106]. For example, an MFA for a metal can cover one or all of the following processes: primary mining and raw material production, fabrication and manufacturing, use of the metal, and EoL management. In most of the models, the use phase is the only process that stores materials, while the other phases transport or transform the materials [106]. An exception to this assumption is the storage of valuable metals, for reasons of financial speculation or ensuring strategic reserves.

A *stock* is a component of a process that includes the material reservoir (mass) stored within that process. Stocks are measured in the physical unit of kilograms. Stocks may increase in size (resulting in the accumulation of materials), decrease in size (resulting in the depletion of materials) or remain constant. Most studies define stock as the *in-use stock* and do not include materials that have been retired and remain somewhere in storage (known as *hibernating stock*), e.g., underground electricity cables [107].

Processes are connected by *flows* (mass per time). The flows of materials entering a process are called *inflows* (i.e. gross demand), while those exiting a process are called *outflows*.

Finally, a *system* consists of a set of the material *flows*, *stocks*, and *processes* within a boundary that is defined in both space and time. The spatial system boundary is typically determined by the geographic area in which the processes are situated. This can include the premises of an organization, a city, a region, a country, a continent or the entire planet. The temporal boundary depends on the type of system being examined and the specific problem being tackled. It is the period over which the system is analysed. For anthropogenic systems, such as an organization, a city or a country, a period of 1 year is typically chosen due to data availability, since the reporting of different types of inventories is usually conducted on an annual basis. For the study of material flows related to the energy transition, which is the focus of this thesis, longer time horizons are required, in order to model decarbonization pathways that are aligned with the Paris Agreement targets.

An MFA entails a systematic assessment of the *flows* and *stocks* of materials within a *system* that is defined in space and time [106]. It is based on the law of conservation of matter [106], such that a material balance of the *inflows*, *stocks*, and *outflows* of resources in a *process* is established. An MFA constructs a comprehensive and consistent dataset of all the *flows* and *stocks* of a specific material within a *system*. Mathematically, at time *t*, the *stock* is a function of the vintaged *inflow* cohorts that materialized until time *t,* with a model memory of their compositions and relative shares in the *stock*. This model memory is a prerequisite for having a *lifespan distribution* for each age cohort and the associated *outflows*. Based on the assumption that all *inflows* depreciate in a similar manner over time, the material *stock* can be expressed as a convolution, as follows:

$$stock = \sum_{\tau=t_0}^{t} inflow(\tau) * L(t-\tau)$$

Thus, the *stock* at a given time *t* is the sum of the shares from past *inflow* vintages (from the beginning of the model at time-step t_0 to the present model time *t*) that have not yet reached their EoL. The proportion of each past *inflow* vintage that is still part of the *stock* is determined using an age-dependent lifetime probability function for the lifetime *L*(*t*), which represents the share of the vintage that is still part of the stock (i.e., it decreases over time, starting at 100% and eventually reaching 0%).

Depending on the temporal *system boundaries*, an MFA can be *static* if it describes a "snapshot" of a system in time or *dynamic* if it describes the behaviour of a system over a period of time [107]. Most static MFAs use a timescale of 1 year and provide some insight into the anthropogenic metabolism of metals, although they do not inform about the dynamic aspects of resource usage and the consequent changes in flows and stocks. In contrast, the dMFA method, developed by Baccini and Bader [108], is commonly utilized to evaluate the historical, current, and future *flows* and *stocks* of metals within the anthroposphere. By providing estimates of past and future *flows*, a dMFA can provide insights into factors that affect resource use and can provide early warnings of associated environmental issues [106]. In addition, it can provide information that is important for infrastructure investment planning along the supply chain of a product or end-use sector, from mining to waste management.

Furthermore, an MFA can be *retrospective*, analysing past *stocks* and *flows* based on historical data, or *prospective*, looking into the future using data extrapolation, or a combination of both approaches.

Depending on whether the aim of the MFA is to estimate the accumulation of resources (*stock*) or the *flows* (*inflows* and *outflows*) and depending on the availability of relevant data for a process, an *inflow-driven* or a *stock-driven* MFA can be conducted. In an *inflow-driven MFA*, given the *inflows* and a lifetime probability function, the *outflows* and *stocks* are calculated, while in a *stock-driven MFA*, given the *stock* and a lifetime probability function, the *inflows* and *outflows* are calculated.

4.1.2 Modelling approach

Making use of the terms defined in Section 4.1.1, this section presents the modelling approach developed in this work, covering the type of MFA developed for this work based on its overall aim and system boundaries. The modelling approach described in this section serves as a basis for addressing *RQs 1–3* of this thesis.

A graphical representation of the model components from **Articles I–IV** that are relevant to the presentation of the results included in this introductory essay is presented in Figure 4.1. Given that the focus of this work is to conduct a study over a period of time, i.e., up to 2050, a dMFA is developed. Central to the models in all the articles appended to this thesis are dynamic stock-driven and inflow-driven MFA models. Given the historical and future (based on scenarios) installed capacities of wind and solar, which are used as the *stock*, a stock-driven MFA is performed that generates the new capacity demand *inflows*. Capacity demand inflows are then converted to material demand inflows using material intensity coefficients. These are then fed into a dynamic inflow-driven MFA, resulting in *outflows* and *in-use stock* for the materials.

Article I develops a dMFA model for wind power that captures the material flows associated with both the replacement of existing capacity and the expansion of wind power capacity over time. The model includes a representation of material intensities, technology lifespans and sub-technology market shares at an aggregated level. The methodology incorporates two CE strategies: longer service lifespan and material intensity reduction, thereby covering the slow and narrow parts of the Slow–Narrow–Close framework and identifies a trade-off linked to their joint implementation. In addition, **Article I** introduces a method to calculate the embodied emissions associated with the concrete and steel used in wind power installations.

Article II builds on the methodological framework established in **Article I** by providing a more-detailed representation of wind power technologies. This includes an expanded set of metals, updated and more-detailed material intensity assumptions, and a refined treatment of the sub-technology market shares and technology lifespans. **Article II** also extends the dMFA framework to include solar power. **Article II** models three technology design-related CE strategies: longer service lifespan, material intesity reduction, and substitution. Thus, it covers the slow and narrow parts of the Slow–Narrow–Close framework and presents a trade-off linked to the joint implementation of slow and narrow strategies.

Article III extends the scope of the CE strategies in **Article II** by incorporating recycling, thereby adding an EoL strategy to the three CE strategies related to the technology design stage. This extension allows the full spectrum of the Slow–Narrow–Close framework to be covered. As a result, the analysis expands from the gross demand, as examined in **Articles I** and **II**, to include the primary material demand and the interactions between these demand types, enabling further investigation of the trade-offs identified in **Articles I** and **II**.

Article IV introduces perspectives from the field of climate justice. It develops a methodology that estimates the allocation of metals based on equity principles. This approach enables a comparison between the required metal production and reserves, under different CE strategies that span the Slow–Narrow–Close framework, and the metal allocations derived from equity principles. Further details on the implementation of equity principles are provided in Section 4.3.

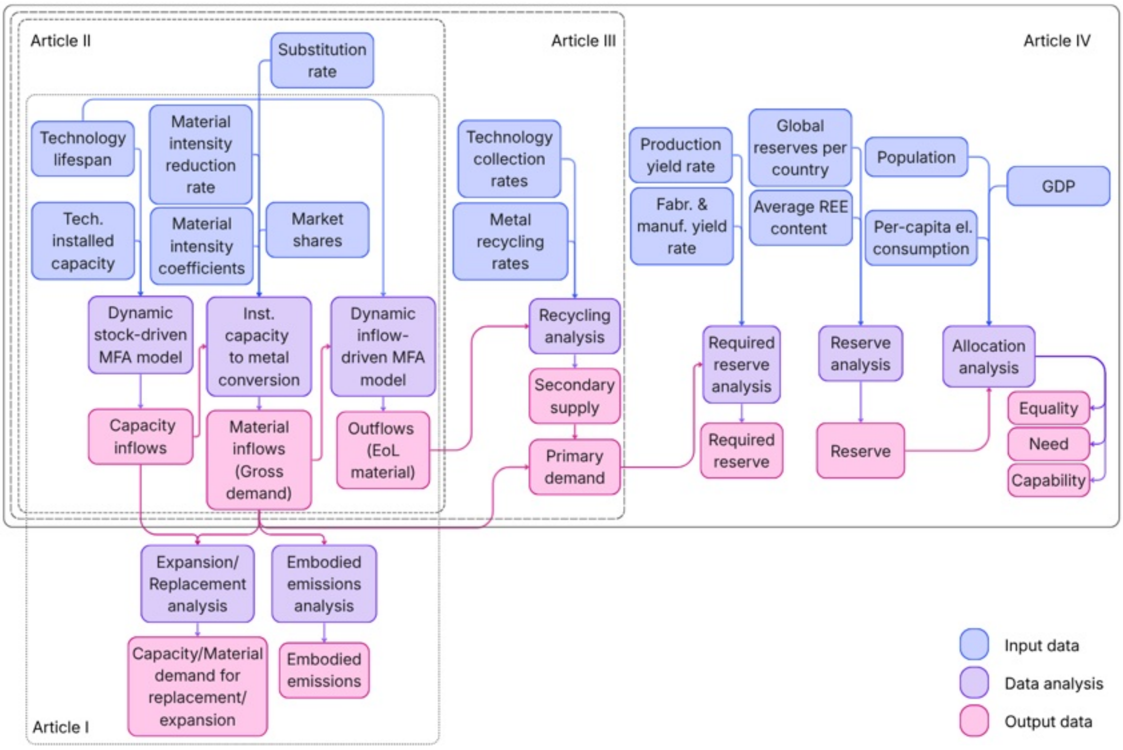


Figure 4.1: Graphical representation of the modelling framework of the introductory essay of this thesis, which includes the necessary components from the model frameworks presented in **Articles I–IV**. Abbreviations: Tech., technology; el., electricity; Inst., installed; Fabr. & manuf., fabrication and manufacturing; GDP, Gross domestic product. Source: Author.

System boundaries

The spatial system boundary for **Articles I–III** is Sweden and for **Article IV** is the EU.

Temporally, the decarbonization scenarios cover the period of 2022–2050, with 2021 as the base year. Since estimating the fractions of older wind and solar power capacity still in operation requires historical commissioning data (see Figure 4.2), the dataset extends back to 1996. Therefore, a *retrospective* MFA model is conducted covering the period of 1996–2021. The *prospective* MFA covers the period of 2022–2050.

Given the end year of the scenarios and the long lifespans of wind and solar technologies, the full lifecycles of the technologies introduced later in the scenario period are not fully captured (Figure 4.2). This makes it difficult to show the full contributions of longer service lifespan and recycling strategies within the temporal boundaries of the analysis, as these effects are expected to continue beyond 2050.

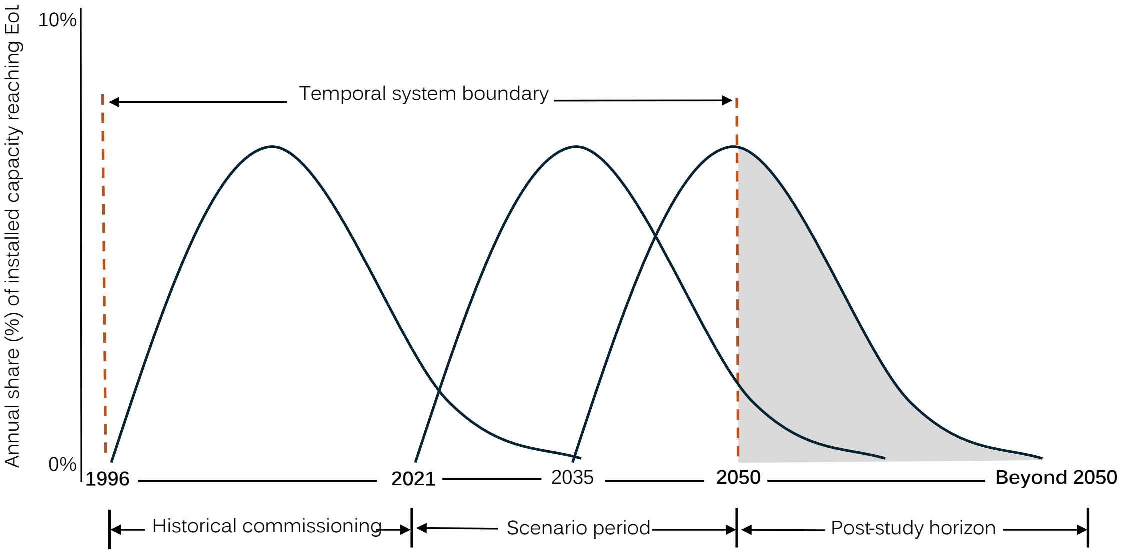


Figure 4.2: Temporal system boundary (1996–2050) and a conceptual representation of the lifespans of the technologies commissioned in different years within this boundary. The figure shows three technology lifespan distributions, expressed as the annual share (%) of installed capacity reaching EoL, for technologies commissioned in 1996, 2021 (the base year), and 2035. While a lifespan distribution exists for every year within the system boundary, only these three are shown for illustration. The figure illustrates that the majority of technologies commissioned in 1996 are decommissioned before 2021, although a small share continues beyond that year in the scenario period. Similarly, most of the technologies commissioned in 2021 are decommissioned within the scenario period, although some extend into the post-study horizon, as indicated by gray shading. For technologies commissioned later in the scenario period (e.g., 2035), a high percentage reaches EoL during the post-study horizon. Source: **Article III**.

4.2 Scenario development

4.2.1 Conceptual basis

Scenario studies can be placed into different categories of scenario development, each addressing distinct questions about the future. Two commonly used categories are *predictive* and *explorative* scenarios, as defined by Börjeson et al. [109].

Predictive scenarios respond to the question: *What will happen?* and thus attempt to predict future developments [109]. They are closely linked to the concepts of probability and likelihood, as they aim to assess the most likely future outcomes under given conditions. Predictive scenarios are often used for planning and adaptation purposes, supporting decision-makers in anticipating foreseeable challenges and opportunities. They can also serve to highlight potential problems that may arise if specific development paths are realized. Such approaches rely on the assumption that future system behaviours can be meaningfully inferred from current knowledge and trends.

Explorative scenarios, in contrast, address the question: *What can happen?* Rather than estimating the most likely outcome, explorative scenarios examine a range of possible future developments from multiple perspectives. Typically, a set of scenarios is developed to span a broad spectrum of potential pathways, often using long-term time horizons to explicitly allow for structural and more-fundamental changes. In many cases, long-term predictions, sometimes referred to as surprise-free scenarios, are used as reference or baseline scenarios in explorative studies [109]. Explorative scenarios are employed as tools to examine the implications of alternative futures and to support strategic decision-making [109].

Predicting future demand for raw materials is highly challenging, if not impossible. The complexity of such analyses may yield multiple possible future outcomes, sometimes leading to a high number of alternative scenarios being examined [110].

In the context of the aims and research questions of this thesis, an *explorative* scenario approach is considered suitable and is adopted in this work. This is described in Section 4.2.2.

4.2.2 Modelling approach

Scenario development in this thesis focuses on the specification and combination of CE strategies, ranging from a baseline without CE intervention to composite strategies that represent the joint implementation of multiple CE measures. Decarbonization scenarios, which describe the assumed development of wind and solar power over time, are used as exogenous inputs to the dMFA. Scenario development related to CE strategies is central to all the appended articles and underpins the analyses conducted to address *RQs 1–3* of this thesis. In addition, **Article I** introduces two embodied emissions narratives to study the effects of CE strategies on embodied emissions, and **Article III** presents results in terms of three sub-technology market-share pathways.

Decarbonization scenarios

Two decarbonization scenarios from the appended articles are used as inputs to the dMFA: one aligned with Sweden's national climate targets and one aligned with EU climate targets. Table 4.1 summarizes the total electricity demand and installed wind and solar capacities in 2050, which is the end year of the scenarios.

The Swedish scenario, which is called Renewable Electrification has been developed by the operator of the Swedish transmission system [111]. It represents an electricity-intensive scenario, with the electricity demand reaching nearly 300 TWh in 2050, from 173 TWh in 2020, driven by electrification of industry and transportation, supported by large-scale deployment of wind and solar power. The scenario prioritizes deep sector integration and the development of a hydrogen economy, with electricity playing a key role in the production and export of fossil-free, energy-intensive products such as hydrogen-reduced iron and climate-neutral cement. Electricity generation is dominated by large-scale wind and solar power, that together account for about 80% of installed capacity by 2050. Onshore wind already accounted for 21% of electricity generation in 2021 and remains a major source, reaching 26% of installed capacity by 2050. Offshore wind and solar currently have minimal shares but are projected to grow substantially, reaching 33% and 22% of installed capacity, respectively. The total installed power capacity reaches 28.2 GW for onshore wind power, 35 GW for offshore wind power, and 22.9 GW for solar power by 2050 (Table 4.1). While electricity systems and decarbonization strategies vary across countries, they commonly involve significant investments in renewable energy and transportation electrification. The RE scenario represents a high-electrification, high-renewables pathway typical of ambitious decarbonization efforts.

At the EU level, the Decarbonising Energy scenario developed by IRENA in collaboration with the European Commission is used [112]. This scenario reflects EU Member States' policies and plans in place as of December 2024 and assumes additional measures to meet the European Commission's objectives in relation to climate mitigation, energy security, and competitiveness. It represents a highly electrified and renewables-driven pathway, with total electricity generation increasing from 2708 TWh in 2021 to 4837 TWh by 2050, of which around 88% is supplied by renewable sources. The expansion of wind power is particularly significant. Installed capacity of onshore wind power grows from 173 GW in 2021 to 517 GW in 2050 (Table 4.1), corresponding to an almost threefold increase. Offshore wind power experiences even more rapid growth, rising from 15 GW in 2021 to 303 GW by 2050 (Table 4.1), representing an approximately twentyfold expansion. This strong deployment of both onshore and offshore wind highlights the central role of wind energy in the decarbonisation of the EU electricity system. Overall, the scenario reflects a large-scale transition toward renewable generation technologies, supported by electrification across sectors and substantial capacity expansion.

Table 4.1: Installed capacities of wind and/or solar power in 2050 in the decarbonization scenarios included in this thesis.

Scenario	Geographic scope	Total electricity demand in 2050 [TWh]	Renewable power installed capacity in 2050 [GW]
Renewable Electrification	Sweden	298	Onshore: 28.2 Offshore: 35 Solar: 22.9
Decarbonising Energy	European Union	4837	Onshore: 517 Offshore: 303

CE strategies

The analysis assesses the effects of four individual CE strategies: longer service lifespan, metal intensity reduction, substitution, and recycling. In addition, three composite strategies are considered. Composite A combines longer service lifespan with material intensity reduction as applied in **Article I**, capturing the slow and narrow effects on material flows. Composite B combines metal intensity reduction, substitution, and recycling as applied in **Articles III** and **IV**, capturing the narrow and close effects on material flows. The third, composite C, combines all four strategies as applied in **Articles II–IV**, including longer service lifespan, thereby reflecting the full Slow–Narrow–Close framework. A baseline strategy, in which no CE strategies are applied, serves as the reference case and entails a continuation of current situation.

The longer service lifespan strategy extends the operational lifetimes of technologies through improved design, thereby reducing replacement rates. Metal intensity reduction reflects decreases in the material content per unit of installed capacity due to improved material efficiency or optimized product design. Substitution refers to the replacement of materials in final applications with alternative materials, components or technologies. Recycling captures the recovery of materials from decommissioned technologies for use as secondary raw materials.

Figure 4.3 provides an overview of the CE strategies considered and their effects on material flows, while Table 4.2 summarizes the key assumptions and parameters for each strategy. Further details are provided in **Articles I–IV**.

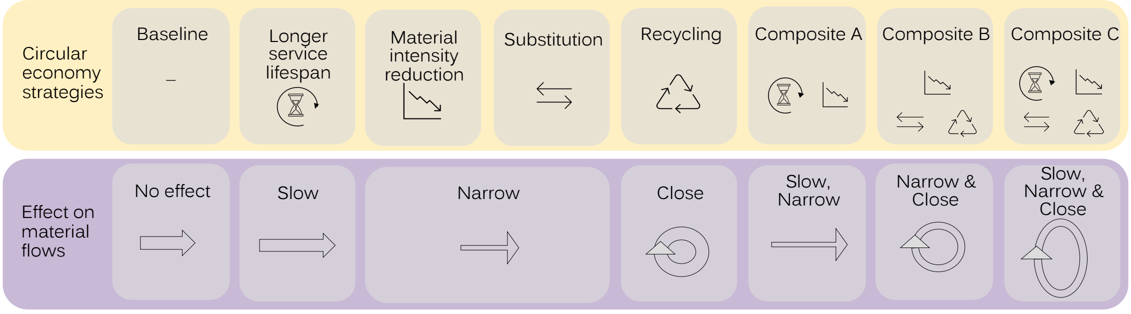


Figure 4.3: CE strategies included in the thesis and their effects on material flows.

Embodied emissions cases

Two emissions factors' narratives are applied: *No emissions change* and *Transformative emissions change*. The *No emissions change* narrative assumes that currently used production processes remain in place throughout the period to 2045, the year by which Sweden has committed to achieving net-zero GHG emissions. In the *Transformative emissions change* narrative, emissions factors decline over time, reflecting the implementation of cradle-to-gate decarbonization measures for iron-reduced steel and climate-neutral cement, as described in Section 2.3. In addition to technological progress toward low process emissions, the emission factors account for changes in the electricity generation mixes, thereby capturing reductions in energy-related GHG intensities. These include emissions associated with the Swedish electricity generation mix, taking into account electricity imports and exports [61]. Details of the emissions factor assumptions are documented in Karlsson et al. [61].

Although not explicitly framed as such in **Article I**, two CE strategies are implemented: longer service lifespan and material intensity reduction. For the purposes of this introductory essay, and to explicitly differentiate the effects of these CE strategies on embodied emissions, the model developed in **Article I** is re-run to generate results for the inflows under each CE strategy considered: longer service lifespan, material intensity reduction, and a composite strategy (composite A), in addition to the baseline. In total, eight cases are analysed, resulting from the combination of the two emissions-factor narratives and the four CE strategies, as illustrated in Figure 4.4.

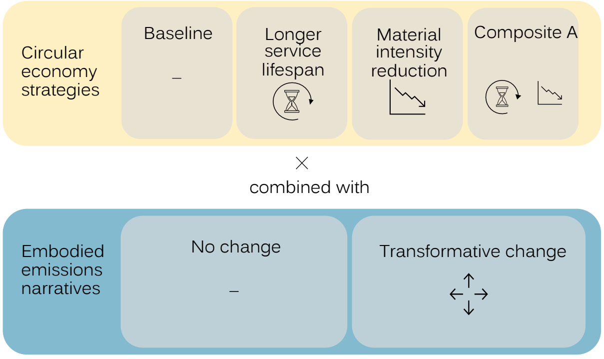


Figure 4.4: Overview of the eight cases analysed resulting from the combination of four CE strategies with two emissions factor narratives. Source: Author.

Market share pathways

The amount of materials in wind turbines and solar panels depends not only on the material intensity of the technologies but also on their market share. In total, three pathways with varying market-shares of the sub-technologies are explored: a ‘central’ pathway, together with two market-share pathways with a diminishing and expanding use of REE-containing PM wind and thin-film solar sub-technologies. In particular, the three pathways developed by the European Commission’s Joint Research Center are used: low market-share (LMS), medium market-share (MMS) and high market-share (HMS) [88]. In 2018, PM turbines (DD-PMSG & GB-PMSG) accounted for approximately 30% of the market-share in the EU onshore wind fleet. They increase to 52%, 59% and 65% by 2050 under the LMS, MMS and HMS pathways, respectively. Offshore wind is already dominated by PM; the HMS preserves this dominance (95% in 2050), while the MMS and LMS drop to 68% and 44% respectively. In 2018, first-generation solar panels held about 95% of the market, while a-Si and CIGS panels accounted for approximately 0.3% and 1.9%, respectively. By 2050, under the LMS, thin films nearly vanish (a-Si: 0%, CIGS: 1%), the MMS yields modest growth (a-Si: 1%, CIGS: 4.5%,), and the HMS sees strong thin-film uptake (a-Si: 3%, CIGS: 10%).

Table 4.2: Main assumptions and input data for the analysed CE strategies. Source: based on **Articles I-III**.

CE Strategy	Longer service lifespan assumptions	Material intensity reduction assumptions	Substitution assumptions	Recycling assumptions
Baseline (Articles I–IV)	Base year mean lifespan: **Article I**: Onshore wind: 20 years Offshore wind: 20 years **Articles II–IV**: Onshore wind: 21.7 years Offshore wind: 23.6 years **Articles II–III**: Solar: 26.3 years Kept constant over the scenario period	Base year metal intensities (kg/MW): **Article I**: DD-PMSG: Neodymium: 165| Dysprosium: 19 Concrete: Onshore: 447000| Offshore: 676000 Steel: Onshore: 155000| Offshore: 289000 **Articles II–IV**: DD-PMSG: Neodymium: 176.6| Praseodymium: 35.3| Dysprosium: 26.6| Terbium: 5.7 GB-PMSG: Neodymium: 34.5| Praseodymium: 6.8| Dysprosium: 5.1| Terbium: 1.3 **Articles II–III**: c-Si: Silver: 36.7 a-Si: Germanium: 45.3 CdTe: Cadmium: 88, Tellurium: 68.5 CIGS: Indium: 18, Gallium: 6.8, Selenium: 41.5 MI reduction rate: 0%	**Article I**: No substitution modelled **Articles II–IV**: Substitution rate: 0%	**Article I** and **II**: No recycling modelled **Articles III** and **IV**: Collection rates: 80% Recycling rates: Neodymium, Praseodymium, Dysprosium, Terbium: 0% **Articles III & Introductory essay**: Silver, Germanium, Gallium, Indium, Selenium: 0% Cadmium, Tellurium: 90%
Longer service lifespan (Articles I–IV)	Mean lifespan in 2050: **Article I**: Onshore wind: 25 years Offshore wind: 25 years **Articles II–IV**: Onshore wind: 30 years Offshore wind: 35 years **Articles II–III**: Solar: 40 years Values linearly interpolated between base year and 2050	Same as baseline	Same as baseline	Same as baseline
Material intensity reduction (Articles I–IV)	Same as baseline	Compound annual growth rates (% per year) between the base year and 2050: **Article I**: Concrete, steel: 0.35 Neodymium, dysprosium: 1.18	Same as baseline	Same as baseline

Table 4.2 cont.

Material intensity reduction (Articles I–IV)	Same as baseline	**Articles II–IV**: Neodymium, Praseodymium: -1.2 Dysprosium, Terbium: -2.4 **Articles II-III & Introductory essay**: Silver: 9.2, Cadmium: 5.5, Tellurium: 4.2, Germanium: 3.8, Indium: 3.3, Gallium: 4.9, Selenium: 3.9	Same as baseline	Same as baseline
Substitution (Articles II–IV)	Same as baseline	Same as baseline	**Articles II–IV**: Substitution rates in end year: Wind: 50% Solar: 20% Values linearly interpolated between the base year and 2050.	Same as baseline
Recycling (Articles III and IV)	Same as baseline	Same as baseline	Same as Baseline	**Articles III–IV & Introductory essay**: Collection rates in end year: Wind: 95% Solar: 85%. Values linearly interpolated between base and end year. Recycling rates in end year (%/year): neodymium, praseodymium, dysprosium, terbium, indium, gallium, sellenium: 90| Germanium: 80|Silver: 94|Cadmium, tellurium:95 Logistic curve was applied between base and end year.
Composite A (Article I)	Same as longer service lifespan	Same as material intensity reduction	-	-
Composite B (Articles III and IV)	Same as baseline	Same as material intensity reduction	Same as substitution	Same as recycling
Composite C (Article IV)	Same as longer service lifespan	Same as material intensity reduction	Same as substitution	Same as recycling

4.3 Equitable metal allocation

4.3.1 Conceptual basis

Equity principles can be expressed through more than one formula, and some formulae are consistent with more than one principle [78,80]. As mentioned earlier equity principles have been extensively applied for carbon budget allocations. This section describes how each principle can be applied when transposed to the domain of metal allocation.

Most commonly, **equality** is applied as an equal-per-capita share of the global carbon budget, with population serving as the sole basis for the allocation [78]. Applied to metals, this means that the more-populous countries receive larger absolute quantities of available metals. It is worth noting that another interpretation holds that those in equal positions are required to contribute equally to addressing a problem [78,82]. Under this interpretation, equality is modulated by the other principles, such as responsibility and capability, and a purely per-capita allocation may itself be considered inequitable if it ignores morally relevant differences between countries.

Applied to the metals used in renewable energy technologies, the **need** principle allocates a larger share of the available metals to countries with lower levels of electrification or renewable capacity, on the grounds that meeting basic needs takes precedence over further consumption in more-developed countries. In practice, implementing a need-based allocation requires a proxy for unmet development needs [79].

Applied to metals, **capability** can be understood as the extent to which countries with greater economic resources can reduce their primary metal demands through energy demand reductions, thereby easing availability pressures. GDP is typically used to represent countries' overall capability to act on climate mitigation. Implementing capability-based allocation relies on current and projected GDP and population data [79]. Different GDP projections reflect assumptions about future economic activity and growth.

4.3.2 Modelling approach

This section describes how the equity principles conceptualized above are operationalized to develop an equitable allocation analysis for metals. The purpose is to assess whether the metal requirements implied by the scenario analysis are compatible with an equitable share of globally available annual metal production and reserves based on the selected principles, or if they imply a disproportionate claim. The analysis further examines the extents to which CE strategies can reduce the metal demand and improve compatibility with the three equity principles. Thus, the modelling approach described in this section addresses *RQ3* of this thesis.

Allocation benchmarks: required annual production and reserves

Two allocation benchmarks are developed: required annual production and required reserves. These benchmarks are derived from the MFA results after accounting for losses across the four phases of the metal lifecycle: production, fabrication and manufacturing, waste management, and recycling. The benchmarks are estimated for each CE strategy considered in the scenario development.

Equity principles and allocation logic

The allocation benchmarks are assessed against equity-based allocations derived from the three selected equity principles of equality, need, and capability. In each case, allocations are calculated by multiplying the global total of available production or reserves by an allocation variable. For both production and reserves, constant and dynamic supply assumptions are applied. Constant supply assumes that current annual production and reserves remain unchanged over the scenario period, while dynamic supply reflects increases in production capacity and reserves over time, consistent with historical trends. Details on rates assumed are provided in **Article IV**. The allocation variable is derived by progressively extending an equal-per-capita allocation through additional weighting factors that represent different need and capability considerations.

Under the **equality principle**, allocations are proportional to each country's share of the global population. This operationalization reflects the interpretation that each individual has an equal entitlement to the use of limited resources, irrespective of geographic or economic context.

The **need principle** builds on the equal-per-capita allocation by weighting population shares using the inverse of per-capita electricity consumption. Per-capita electricity consumption is used as a proxy for development status, given its strong associations with access to basic services and socio-economic well-being.

The **capability principle** further extends the equal-per-capita allocation by weighting population shares using the inverse of per-capita GDP. Under this principle, lower-income countries receive a relatively larger allocation, reflecting differences in economic capacity to invest in demand reduction measures and CE strategies. GDP is expressed in purchasing power parity terms and is used as a proxy for overall financial capacity.

Further details on formulas applied, key assumptions and parameters for each principle are provided in **Article IV**.

CHAPTER 5

Embodied emissions

This chapter presents and discusses the results obtained from the research in **Article I** appended to this thesis, as well as from the further analyses conducted for the thesis as described in Chapter 4, *Methodology*. It addresses the *RQ1* of this thesis.

Figure 5.1 presents the annual and cumulative embodied CO_2e emissions from steel and concrete required for wind turbines and their foundations over the period 2022–2045, with 2045 corresponding to Sweden's net-zero GHG emissions target year. Results are shown for eight analytical cases, derived from the combination of two emission-factor narratives and four CE strategies. The decarbonization scenario used as input for the results presented in this chapter is Renewable Electrification, which represents a scenario with large-scale wind power deployment in which electricity plays a key role in the production and export of fossil-free energy-intensive products such as hydrogen-reduced iron and climate-neutral cement in Sweden.

5.1 Annual and cumulative embodied emissions

On an annual basis (Figure 5.1a), the baseline case under the *No emissions change* narrative, that is, without decarbonization in steel and concrete supply chains and without CE strategies in the wind sector, results in embodied emissions of 2.27 $MtCO_2e$ in 2045. This corresponds to an increase of 546% relative to base year (2021) levels and is equivalent to approximately 5% of Sweden's total national emissions in 2021. As electricity generation becomes progressively less carbon-intensive under this narrative, the share of embodied emissions associated with wind technologies increases over time and exceeds the operational emissions from electricity generation by 2040 (Figure 5.1a).

Applying CE strategies under the *No emissions change* narrative reduces annual embodied emissions in 2045 by 9%, 24%, and 30% under the material intensity reduction, longer service lifespan, and composite A strategies, respectively, compared to the baseline. Under the composite A strategy, embodied emissions in 2045 still represent a 382% increase relative to 2021, accounting for around 3% of Sweden's total national emissions in that year. Relative to the baseline, the crossover point at which embodied emissions exceed the operational emissions from electricity generation is delayed by three years, occurring in 2043.

Under the *Transformative emissions change* narrative, the relative reduction potentials associated with the CE strategies remain comparable, with reductions of 9%, 24%, and 30% for the material intensity reduction, longer service lifespan, and composite A strategies, respectively. However, absolute embodied emission levels are substantially lower, amounting to only 0.06%–0.08% of current national emissions by 2045.

In both the *No Emissions Change* and *Transformative Emissions Change* narratives, material intensity reduction provides slightly greater emission reductions than longer service lifespan during the early period, up to 2032, although this difference is hardly visible in Figure 5.1a because the differences are relatively small. After 2032, this pattern reverses, and longer service lifespan becomes more effective, leading to substantially larger emission reductions by 2045.

On a cumulative basis (Figure 5.1b), under the *No emissions change* narrative, the material intensity reduction, longer service lifespan, and composite A strategies reduce cumulative embodied emissions by 5%, 6%, and 10%, respectively, relative to the baseline. Under the *Transformative emissions change* narrative, the corresponding cumulative reductions are 3%, 4%, and 7%.

Overall, longer service lifespan shows a stronger potential for reducing embodied emissions associated with the steel and concrete used in wind power than material intensity reduction during the energy transition. One reason for this difference is that material intensity reduction potential for structural materials is rather low compared to technology-specific materials, with studies showing low to no reduction historically [113]. Therefore, a moderate reduction compared to the base year values is assumed by 2050 (see Table 4.2 in Chapter 4, *Methodology*), in line with previous studies [114].

Their combination, which captures the slow and narrow effects of the Slow–Narrow–Close framework, exhibits a strong potential to reduce both annual and cumulative embodied emissions from steel and concrete. Nevertheless, despite the contribution of these CE strategies, emission reductions in cradle-to-gate processes, particularly in material production, remain essential for wind power to align with Sweden's decarbonisation target.

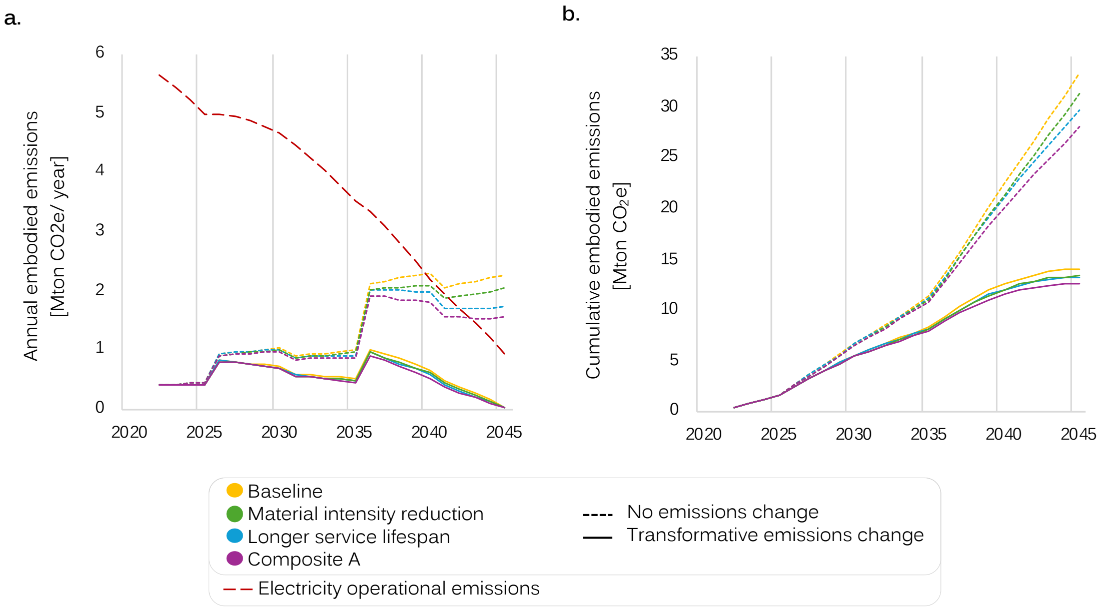


Figure 5.1: Embodied emissions associated with the steel and concrete used in wind turbines and their foundations, shown for the eight cases resulting from the combination of CE strategies and emission factor narratives, on a. annual and b. cumulative bases. Operational emissions from electricity generation are included in the annual results for comparison. Scenario, geography: Renewable Electrification, Sweden. Source: **Article I**, with additional analysis

5.2 Emission factors and consistency

When applying emission factors in dMFA studies that incorporate CE strategies, care must be taken to avoid double counting emission reductions. This risk arises when emission factors already embed mitigation measures that overlap with CE strategies explicitly modelled within the MFA, such as material efficiency, substitution, or recycling. It is also important to ensure consistency between the assumed electricity-generation scenario underpinning the emission factors and the decarbonization scenario used to derive installed wind power capacity, within the MFA model.

Against this background, the emission factors used in this study were drawn from Karlsson et al. [61], who present several alternative cradle-to-gate emission factor narratives based on different combinations of emission reduction measures. Two of these narratives explicitly include material efficiency as an abatement option. Applying such narratives in combination with the material intensity reduction CE strategy implemented in the MFA would result in double counting. Therefore, emission factor narratives that do not assume material intensity reduction or any other CE strategy were selected, since material intensity reduction is explicitly represented within the MFA model itself. While double counting can also arise when other CE strategies, such as substitution or recycling, are modelled, the MFA framework developed in **Article I** does not include recycling, and the emission factors used do not include any CE strategy, avoiding this issue in the present analysis.

Finally, alignment between the electricity-generation assumptions embedded in the emission factors and the decarbonization scenario determining wind power capacity expansion was ensured. Both are based on a decarbonisation scenario in which electricity plays a central role in enabling hydrogen-reduced iron production and climate-neutral cement, ensuring internal consistency across the modelling framework.

5.3 Addressing *RQ1*

This section directly addresses the *RQ1* which is examined in this chapter.

RQ1: To what extent can CE strategies reduce the embodied emissions associated with structural materials for wind turbines and their foundations during the energy transition?

The results show that CE strategies can reduce embodied emissions associated with steel and concrete in wind power turbines and their foundations to a meaningful extent, although their overall effect remains limited relative to the scale of wind power expansion. In the absence of CE strategies and emission reduction measures in the steel and concrete production industries, embodied emissions associated with wind power grow by 546% between base year and 2045. CE strategies reduce annual embodied emissions by up to 30% by 2045 under the composite strategy, while individual strategies achieve more moderate reductions. On a cumulative basis, reductions are smaller, ranging from approximately 5–10% under the no emissions change narrative and 3–7% under the transformative narrative. This indicates that while CE strategies can effectively lower embodied emissions, their influence on cumulative emissions over the transition period is more limited.

The effectiveness of CE strategies differs both across strategies and over time. The temporal pattern shows that longer service lifespan initially delivers slightly lower emission reductions than material intensity reduction, but this relationship reverses over time. Both longer service lifespan and material intensity reduction are design-based strategies, implemented in newly installed turbines from the beginning of the scenario period. However, their effects differ in timing. Material intensity reduction leads to immediate emission reductions, whereas extending service lifespan has a delayed effect. Although it is applied at commissioning, its effect only becomes visible once the turbines reach their EoL.

Longer service lifespan emerges as the most effective individual strategy for reducing embodied emissions from structural materials. This reflects the limited potential for material intensity reduction in steel and concrete, where historical trends and technical constraints suggest only modest improvements. As a result, among the strategies explored, extending the lifetime of wind turbines and their foundations provides a comparatively stronger mechanism for reducing total material demand and associated emissions over time. In contrast, material intensity reduction, while effective in principle, delivers smaller gains due to the relatively low reduction potential for these materials within the timeframe considered.

Despite these contributions, the analysis highlights that CE strategies alone are insufficient to achieve deep reductions in embodied emissions. Under the no emissions change narrative, embodied emissions increase substantially as a result of large-scale wind power deployment, even when CE strategies are applied. This reflects a scaling effect: rapid expansion of wind power drives high material demand, limiting the relative effect of CE strategies. Consequently, decarbonisation of steel and cement production processes is essential for aligning embodied emissions with climate targets.

At the same time, the results demonstrate that the effectiveness of CE strategies is highly dependent on the emissions intensity of material production. Under the transformative emissions change narrative, absolute embodied emissions are drastically reduced, and the relative contribution of CE strategies becomes less significant in absolute terms. This underscores that supply-side decarbonisation is the dominant driver of emission reductions, while CE strategies play a complementary role by reducing material demand.

Overall, the extent to which CE strategies can reduce embodied emissions is substantial but inherently limited. CE strategies contribute to lowering material demand and associated emissions growth, particularly through longer service lifespans, but they cannot offset the emissions associated with large-scale wind power deployment on their own. Achieving substantial reductions in embodied emissions requires an integrated approach that combines demand-side measures with deep decarbonisation of material production systems.

CHAPTER 6

Material demand

This chapter, which draws on the work presented in all appended articles and constitutes the core analytical contribution of the thesis, presents and discusses the results associated to *RQ2*. Addressing this research question requires an analysis of several interrelated aspects, including a comparison of individual and combined effect of CE strategies, an assessment of differences in their magnitude and temporal dynamics over the scenario period, and an identification of potential trade-offs arising from CE strategies joint implementation. Results are presented in terms of installed capacity, gross material demand, or primary material demand, depending on which metric is most appropriate for the analysis and the appended article from which the results are drawn.

Before synthesizing the results on the individual and combined effects of CE strategies on material demand, Section 6.1 introduces the dynamic material flow analysis (dMFA) results for installed capacity requirements under the baseline strategy, which assumes no CE implementation. The purpose of this section is to illustrate the overall magnitude of the energy transition. Section 6.2 then synthesizes the effects of CE strategies on the demand for structural materials, followed by an analysis of demand and supply requirements for technology-specific materials in Section 6.3. Finally, Section 6.4 directly addresses *RQ2* of the thesis. Across all sections, results are presented and discussed in terms of both magnitude and temporal dynamics, for individual strategies as well as their combined effects, building on analyses reported in **Articles I–IV**.

Results for Sweden are based on the Renewable Electrification scenario, while results for the European Union rely on the Decarbonising Energy scenario.

6.1 Installed capacity

This section synthesizes results as modelled for the purposes of this thesis based on the model from **Article I**. Figure 6.1 shows the estimated newly installed capacities grouped in 5-year periods for onshore, offshore, and total wind capacity in the baseline strategy in Sweden. The five-year installed capacity is divided into expansion, and replacement demands in the upper graphs, while the lower graphs show the growth and depreciation dynamics of the newly installed generating capacity by age cohorts (5-year periods) over time.

This thesis focuses on the energy transition period, which reflects the period during which the deployment of renewable technologies is expected to be the largest to meet decarbonization targets. Indeed, Figure 6.1 shows that substantial increases in capacity requirements are needed during this period. Historically and up to 2021, the base year of the analysis, the largest newly installed capacity of wind was in 2021 with 2.1 GW [115]. Looking at the total wind capacity requirements, the maximum newly installed capacity under the baseline strategy, which is reached in the period of 2040–2045 with 20 GW. This equates to an average annual installed capacity of 4 GW, which is equivalent to a 90% increase compared to the 2021 newly installed capacity.

At the same time, given that Sweden, has an earlier target year for its for its net-zero emission target compared to EU (2045), and that the scenario period covers up to 2050, the results of this analysis reflect an interesting dynamic. Looking at the total wind power capacity requirements, a decreasing trend of total installed capacity requirements can be observed for the last 5 years of the period, post-2045, indicating that following the achievement of the climate targets, the installation rate of renewable technologies is expected to lower. The material dynamics of this trend are described in the following sections, along with the effects of CE strategies.

Looking at the composition of the demand for wind power capacity requirements, there are considerable changes in the needs for expansion and replacement throughout the scenario period, and between onshore and offshore wind power. For onshore wind turbines, during the historical period and up to 2025, expansion is the main driver of the demand, and the need for replacement is negligible. However, post-2025, the demand for replacing wind turbines that are reaching their EoL becomes increasingly larger and the main driver of newly installed capacity as early as 2030. By the end of the scenario period (2045–2050), replacement accounts for about 80% of the demand for new onshore capacity. This highlights the need for planning for the large-scale replacement of onshore wind turbines, something happening for the first time since the beginning of the wind power industry, making this result important for stakeholders across the EoL management of onshore wind turbines and in countries that follow a similar wind power trajectory as Sweden.

The compositions of the capacity additions for offshore wind turbines follow a different path than the onshore wind capacities. Given the negligible investments made in offshore wind capacity to date in Sweden, the majority of demand up to 2050 is for the expansion of generating capacity. The need for replacement of offshore wind power capacity that is reaching its EoL does not become apparent until the very end of the scenario period. Still, during the last 5 years of the scenario period it accounts for about 38% of the demand for new offshore capacity. Furthermore, given that the majority of investments for the expansion of offshore wind power are introduced from 2035 and onwards, as shown in the growth and depreciation dynamics graph of the newly installed offshore capacity, the need to replace wind turbines reaching EoL post-2050 is expected to become even more dominant. Overall, expansion is the main driver for new installed capacity making this finding relevant for stakeholders in the installation of offshore wind turbines.

The specific magnitude and timing of the expansion and replacement needs are affected by the CE strategies, as illustrated by the comparison between Figure 6.1 and Figure 3 in **Article I**; however, the general trends synthesized above persist.

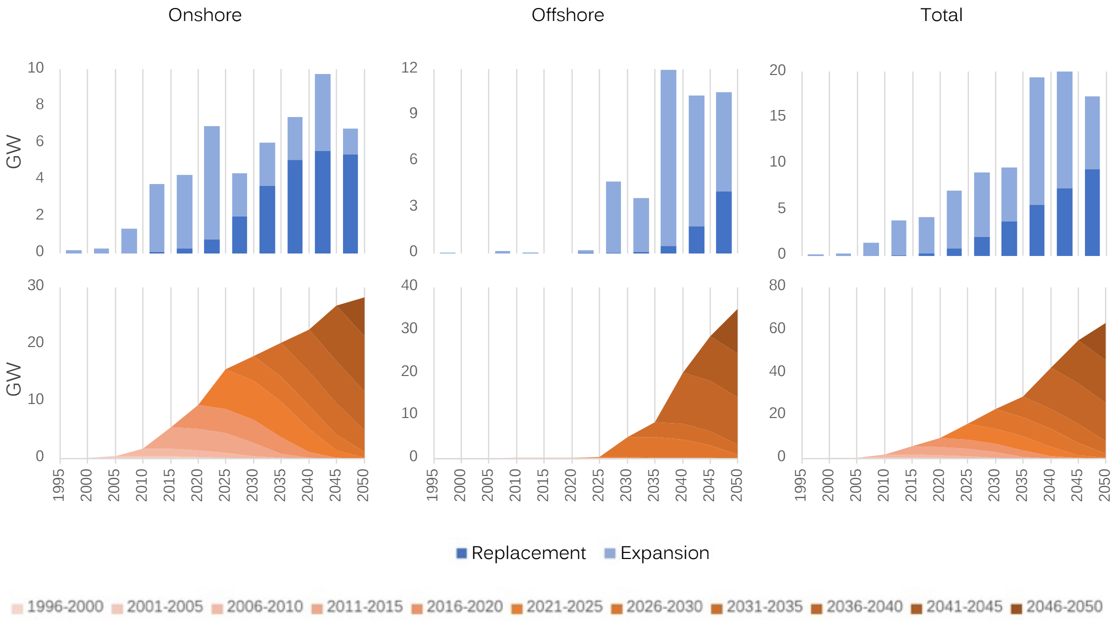


Figure 6.1: Quinquennial (5-year) newly installed generating capacity for the period 1995–2050 for the purposes of replacement and expansion, and the corresponding growth and depreciation dynamics of the capacity over time, with age cohorts (5-year) indicated with different shades of orange and onshore, offshore, and total wind power under the baseline strategy. Scenario, geography: Renewable Electrification, Sweden. Source: **Article I**, with additional analysis.

6.2 Structural materials

Results in this section are based on the model framework and assumptions presented in **Article I**. **Article I** presents the composite A strategy only. Here the results are shown for longer service lifespan and material intensity reduction strategies, as well as their joint implementation in the composite A strategy, alongside the baseline strategy (see Figure 4.3 and Table 4.2 for more details on the strategies).

Figure 6.2 presents material inflows (i.e. gross material demand), including expansion and replacement inflows, and material outflows for structural materials, steel and concrete, over the scenario period under the different CE strategies. All values are reported in metric tonnes, hereafter referred to as tons. First results are presented for the baseline, with the purpose to show the material dimension of the overall magnitude of the energy transition, followed by the extent to which CE strategies can alleviate the material demand.

Figure 6.2 illustrates that the substantial increases in installed capacity reported in Figure 6.1 lead to corresponding increases in material inflows. In the baseline strategy, annual steel inflows increase by approximately a factor of six by 2040, the year with the highest demand during the scenario period, rising from around 0.16 Mtons/year in 2020 to approximately 0.95 Mtons/year. This initial level of steel demand in 2020, based on observed installed capacity in that year, corresponds to about 5% of Sweden's apparent steel use that year, defined as deliveries minus exports plus imports [116]. Under the baseline strategy, the annual steel requirement for wind turbines in the year with the highest demand, 2040, is projected to reach up to 31% of Sweden's total steel use in 2020.

Annual concrete demand in the baseline strategy reaches its maximum value of 2.4 Mtons in 2040. Compared to concrete demand for new wind power construction in 2020, this represents an increase by roughly a factor of five. Total cement use in Sweden amounted to approximately 2.8 Mtons in 2019 [117]. Assuming a cement share of 14% in concrete [118], total concrete use in Sweden that year is estimated at around 20 Mtons. Consequently, peak annual concrete demand for wind power during the scenario period corresponds to roughly 12% of Sweden's 2019 concrete use.

The maximum inflows for steel are reduced by 8%, 9%, and 17% under the effects of material intensity reduction, longer service lifespan, and their joint implementation in composite A compared to the baseline. For concrete, the reductions are at 8%, 10%, and 18%. Under the effects of material intensity reduction, longer service lifespan, and composite A, the total steel and concrete inflows are reduced by 7%, 10%, and 16% compared to the baseline strategy.

While remaining lower than the inflows, the outflows of steel and concrete from decommissioned turbines increase from low levels in 2020 to substantial levels by 2050. In the baseline strategy, the steel annual outflow increases from 0.01 Mtons in 2020 to 0.46 Mtons in 2050. This is equivalent to 15% of the apparent steel use in Sweden in 2020. From roughly 0.036 Mtons in 2020, the annual concrete outflows are estimated to be 33 times larger (1.17 Mtons) in 2050 compared to 2020. This is equivalent to 6% of the concrete used in Sweden in 2019.

Longer service lifespan has a substantial effect on material outflows, reducing steel and concrete outflows by around 31% throughout the scenario period. This is because longer service lifespan strategy shifts outflows in time. In contrast, material intensity reduction has only a minor effect, reducing steel and concrete outflows by about 2%. While material intensity reduction has an immediate effect on material inflows, it’s effect on outflows is delayed until the wind turbines are decommissioned. Throughout the scenario period in the material intensity reduction and composite A strategies, outflows are consistently higher than the demand for replacement, since the decommissioned older turbines are replaced with new turbines with improved technologies that require less materials per installed capacity. This difference however is small given that the assumed low material intensity reduction.

Figure 6.2 shows that toward the end of the scenario period, material outflows from steel and concrete increase, while inflows decline. In principle, this trend suggests growing potential for closing material loops, provided that EoL material flows can be effectively recovered and processed into secondary material supply. However, the extent to which this potential can be realized differs substantially between steel and concrete due to current recycling practices and technological constraints.

Steel is already characterized by a relatively mature and well-established recycling system. Globally, steel achieves high EoL recycling rates, and secondary steel production via electric arc furnaces is widely practiced. As a result, increasing steel outflows toward the end of the scenario period could, in principle, be redirected into existing or expanded recycling capacity, supporting higher recycling. Nevertheless, realizing this potential still requires timely investment and planning, particularly to ensure sufficient scrap collection, sorting, and processing capacity that meets quality requirements for low-carbon steel production.

Concrete, by contrast, is recycled primarily through downcycling. EoL concrete is typically crushed and reused as aggregate in low-grade applications such as road base or backfilling, while the cement fraction is largely lost. Recycling rates by mass may appear high, but material recycling remains limited because recycled concrete rarely substitutes for primary cement, which is responsible for the majority of concrete’s emissions. Although emerging technologies for cement recovery and clinker substitution exist, these remain at an early stage of deployment [61]. Consequently, increasing concrete outflows toward the end of the scenario period do not automatically translate into contributing to closing material loops under current recycling practices.

Given that recycling infrastructure, industrial processes, and regulatory frameworks require long lead times to develop, the results highlight the importance of planning well in advance for EoL management of steel and concrete streams. For steel, planning efforts could focus on scaling and decarbonizing existing recycling systems, while for concrete, more transformative innovations and policy support would be required to move beyond downcycling and enable higher-quality material recovery. Without such anticipatory measures, the increasing material outflows projected toward the end of the scenario period risk remaining underutilized from a CE perspective.

A similar trend between increasing outflows and declining inflows is also observed for technology-specific materials, as presented in **Article I**. In contrast to structural materials, recycling of technology-specific materials covered in the analysis is currently negligible (see Table S1.1 in Supplementary material of **Article II**). As a result, the increasing material outflows expected toward the end of the scenario period represent a largely unrealized resource potential under present conditions. This further underscores the importance of early planning and targeted development of recycling capacity and recovery technologies in order to enable future utilization of these outflows. These dynamics and their implications for secondary supply are explored in greater detail in the following section, Section 6.3.

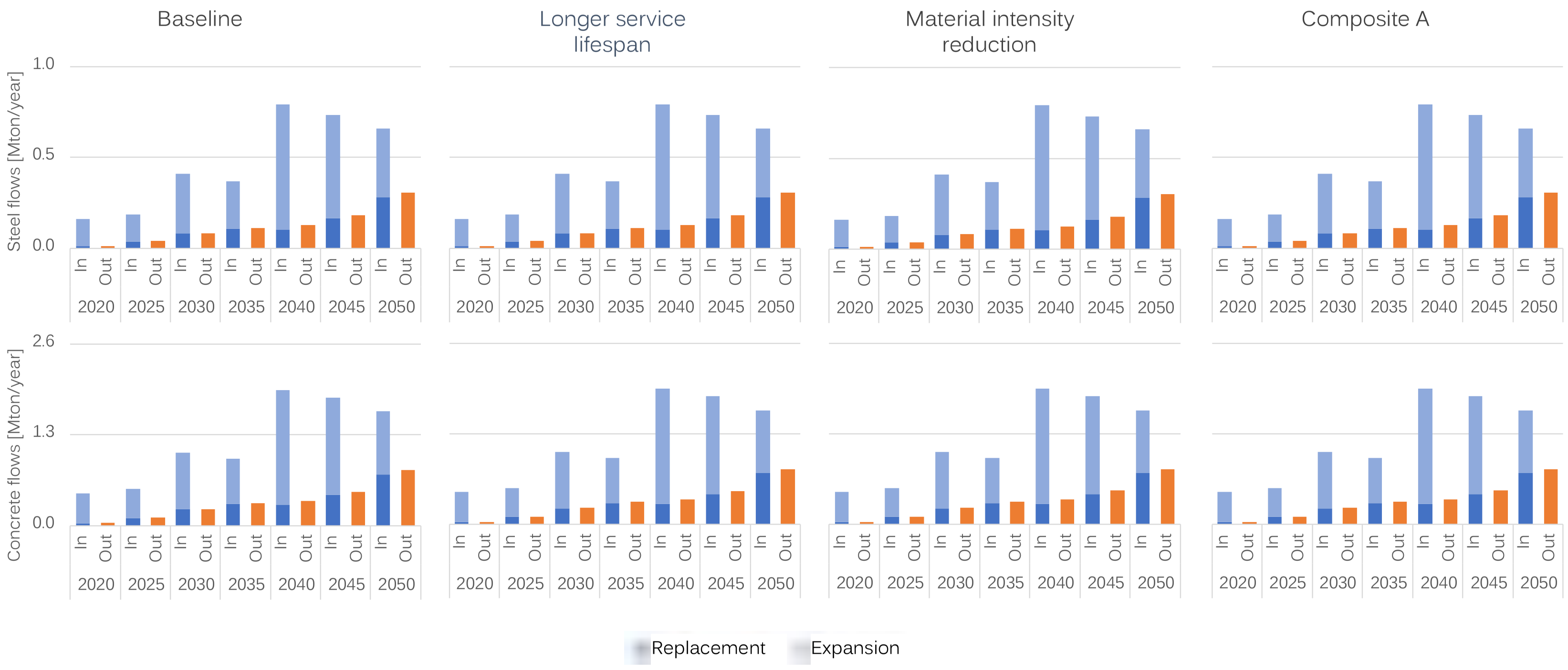


Figure 6.2: Material inflows (gross demand) associated with newly installed capacity for replacement and expansion, and material outflows from decommissioned capacity, for selected years between 2020 and 2050. Results are shown for the baseline, longer service lifespan, material intensity reduction, and composite A strategies, distinguishing structural materials (steel and concrete) and technology-specific materials (neodymium and dysprosium). Scenario, geography: Renewable Electrification, Sweden. Source: **Article I**, with additional analysis.

6.3 Technology-specific materials

6.3.1 Cumulative primary demand

This section builds on **Articles II** and **III** and investigates how CE strategies affect the cumulative primary demand for the eleven technology-specific metals associated with wind and solar power technologies. **Article II** quantifies gross metal demands (inflows) under the CE strategies analysed, while **Article III** introduces the recycling analysis, thereby enabling the assessment of primary metal demand, accounting for secondary material supply through recycling.

Figure 6.3 presents cumulative primary metal demands over the period 2022–2050 for the baseline strategy, together with the reduction potentials achieved by the five CE strategies relative to the baseline; longer service lifespan, material intensity reduction, substitution, recycling, and composite C.

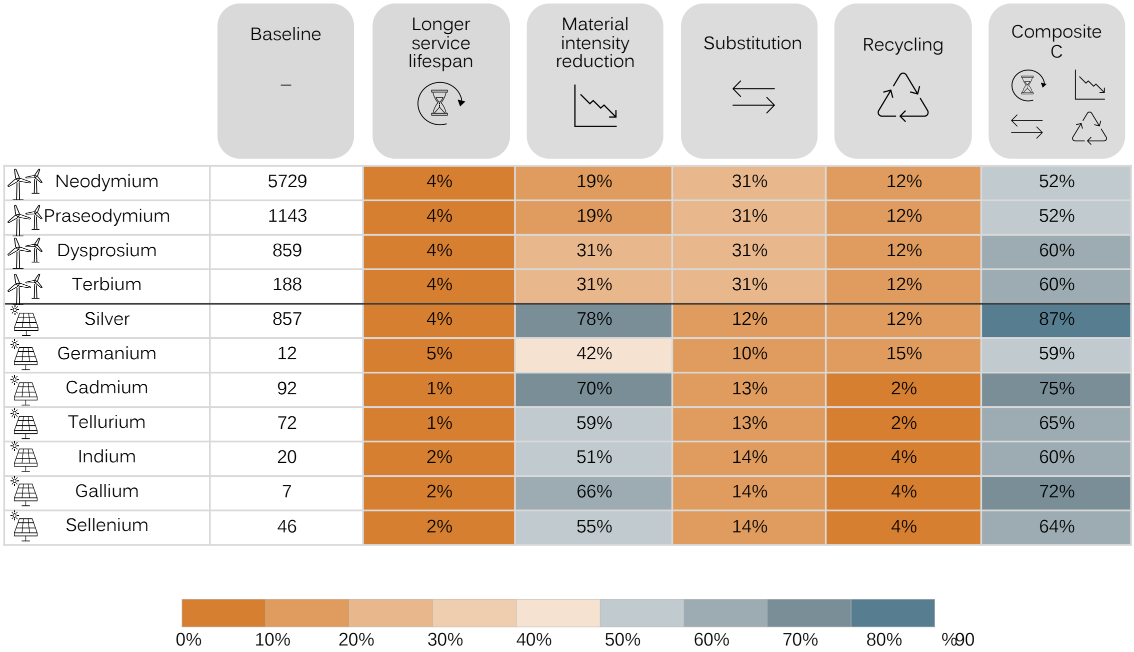
The effects of the CE strategies differ substantially between wind and solar technologies. For wind power, substitution yields the largest reduction in cumulative primary demand for the LREEs neodymium and praseodymium. For the HREEs dysprosium and terbium, substitution and material intensity reduction contribute equally to demand reductions. Averaged across all four REEs, the reduction potentials amount to 4% for longer service lifespan, 12% for recycling, 25% for material intensity reduction, and 31% for substitution.

In solar power technologies, material intensity reduction clearly dominates as the most effective CE strategy for reducing cumulative primary metal demand. For the remaining strategies, reduction potentials vary across individual metals. When averaged across the seven minor metals used in solar power, longer service lifespan, recycling, substitution, and material intensity reduction lead to cumulative demand reductions of 3%, 6%, 13%, and 60%, respectively.

A comparison between Figure 6.3 and Table 3 in appended **Article II**, which reports reduction potentials in terms of gross demand rather than primary demand, reveals that baseline values and reduction potentials under longer service lifespan, material intensity reduction and substitution strategies are identical for all metals except cadmium and tellurium. This indicates that, under current recycling assumptions, reducing gross metal demand is effectively equivalent to reducing primary metal demand for most metals considered. The only exceptions are cadmium and tellurium, for which recycling already plays a significant role.

The divergence observed for cadmium and tellurium reflects the characteristics of the CdTe photovoltaic sub-technology in which these metals are used. Cadmium is a regulated toxic heavy metal, and CdTe modules are therefore subject to hazardous substance regulation and mandatory separate collection in many jurisdictions, including under frameworks such as the EU Waste Electrical and Electronic Equipment (WEEE) Directive. These regulatory requirements, combined with mature and efficient recycling processes, result in high collection and recycling rates for both cadmium and tellurium, ensuring that a substantial share of these metals is recovered rather than dissipated after EoL.

The composite C strategy demonstrates that, when combined, CE strategies can reduce cumulative primary metal demand between 2022 and 2050 by more than half for all metals studied, compared with the baseline. The corresponding reductions range from 52% to 87%. Silver, cadmium, and gallium exhibit the highest cumulative reduction potentials, each exceeding 70%, with silver in particular reaching an 87% reduction. Overall, the combined application of slow strategies (longer service lifespan), narrow strategies (material intensity reduction and substitution), and close strategies (recycling) shows a strong potential to substantially reduce cumulative primary metal demand during the energy transition period.



	Baseline –	Longer service lifespan	Material intensity reduction	Substitution	Recycling	Composite C
Neodymium	5729	4%	19%	31%	12%	52%
Praseodymium	1143	4%	19%	31%	12%	52%
Dysprosium	859	4%	31%	31%	12%	60%
Terbium	188	4%	31%	31%	12%	60%
Silver	857	4%	78%	12%	12%	87%
Germanium	12	5%	42%	10%	15%	59%
Cadmium	92	1%	70%	13%	2%	75%
Tellurium	72	1%	59%	13%	2%	65%
Indium	20	2%	51%	14%	4%	60%
Gallium	7	2%	66%	14%	4%	72%
Sellenium	46	2%	55%	14%	4%	64%

Figure 6.3: Baseline values and percentage reductions in cumulative primary metal demand under CE strategies relative to the baseline, for REEs in wind power and minor metals in solar power, 2022–2050 (tons). Scenario, geography: Renewable Electrification, Sweden. Source: **Articles II** and **III**.

6.3.2 Annual primary demand

This section investigates the temporal dynamics of CE strategies on the primary metal demand for the eleven technology-specific metals associated with wind and solar power technologies over the scenario period. Figure 6.4 shows the annual primary metal demands for the 2022-2050 period per CE strategy for these metals. Observed discontinuities in the time series correspond to historical step changes in installed capacities, and the five-year intervals used in the prospective installed capacity data.

Effects of individual CE strategies

The effects of the CE strategies vary across technologies, metals, and over time. For the LREEs neodymium and praseodymium (Figure 6.4a–b), recycling reduces primary demand less than material intensity reduction for most of the scenario period; however, its effect increases toward the end, surpassing material intensity reduction from 2046 onward. For the HREEs dysprosium and terbium, material intensity reduction and substitution exhibit consistently strong and comparable reduction potentials throughout the scenario period.

For solar power, material intensity reduction is the CE strategy that has by far the largest potential for decreasing the annual metal demands. For the other CE strategies, differences exist among the metals and along the scenario period. Substitution follows material intensity reduction with the second-largest reduction potential throughout the scenario period for all metals except silver (Figure 6.4e) and germanium (Figure 6.4f). It follows the same trend for silver and germanium until 2043 and 2041 respectively, but following these years, recycling shows larger reduction potential. For germanium, primary demand under the longer service lifespan strategy also becomes lower than in the substitution strategy from 2048 onwards. While longer service lifespan is the strategy with the weakest potential for metals in both wind and solar technologies and for most of the scenario period, given the long lifespans of wind and solar technologies, the potential of this strategy would continue to increase beyond the scenario end year. This is especially the case for offshore wind and solar, which in contrast to onshore wind are introduced later in the studied period (Figure 2 in appended **Article II**).

Some of the CE strategies lower the primary demands in a certain year in the scenario period under base year (2021) demand levels for some metals, despite the large increase in the renewable technologies installed capacity. For solar power (Figure 6.4e-k), material intensity reduction alone results in lower-than-base-year demand levels for silver and germanium well before the end of the period. Under this single strategy, demand stays below the 2021 levels for most of the scenario period, leading to reductions of 80% for silver and 56% for germanium by 2050. Under this CE strategy, the primary demand for cadmium (Figure 6.4g) is also reduced to lower-than-base-year levels. This occurs in 2040 and by 2050 the reduction is at 34% compared to 2021. For wind power (Figure 6.4a-d), no single CE strategy is sufficient to attain a primary demand that is lower than the base year levels at any timepoint in the scenario period.

Overall, some trends on the effects of individual CE strategies emerge; for solar power, material intensity reduction shows the strongest potential to lower primary metal demand, consistent with previous studies [119,120]. For wind power, substitution is the strategy with the strongest potential, followed by material intensity reduction. Overall, strategies that narrow material flows demonstrate the greatest reduction in metal demands for both wind and solar power during the energy transition.

Effects of joint implementation of CE strategies

Compared to the baseline strategy, the composite C strategy shows that during the scenario period, for wind power, LREEs and HREEs achieve 90% and 97% reductions in primary demand, respectively, in 2050. For solar power metals, the reduction is in the range of 77%–117%. Compared to the base year demand, for wind power, while no single CE strategy is sufficient to attain a primary demand that is lower-than-base-year levels throughout the scenario period, a lower-than-base year primary demand is achieved for all the REEs in the composite C strategy toward the end of the period. For the LREEs (Figure 6.4a-b), a lower-than-base-year is achieved from 2047 onwards and by 2050 it reaches 40% reduction compared to the base year demand. The reduction in primary demand for HREEs (Figure 6.4c-d) reaches lower-than-base year level from 2046 onwards, and by 2050, demand reductions of 84% and 85% are attained for dysprosium and terbium, respectively. For solar power, the primary demands for silver and germanium in the composite C strategy are eliminated by 2043 and 2046, respectively, which means that the secondary supply can cover the entire gross metal demand within the system and can potentially also be used for other applications. For cadmium, the composite C strategy achieves a 68% reduction in the primary demand compared to its base year demand level. For the remaining four metals (used for the CdTe and CIGS sub-technologies), lower-than-base year primary demand levels are not achieved under any strategy throughout the period.

Overall, the joint implementation of longer service lifespan, material intensity reduction, substitution, and recycling, that span the Slow-Narrow-Close framework exhibits a strong potential to reduce the annual primary metal demands, and even eliminates it for some metals, during the energy transition period.

At the same time, while the CE strategies can significantly reduce primary metal demand, primary demand for most metals persist throughout the scenario period, indicating that additional primary or other secondary supplies will still be necessary. In other words, the CE strategies alone are not sufficient to satisfy the increasing material demand during the energy transition. This suggests that in order to meet climate targets as currently modelled in decarbonization scenarios, there is a need to expand metal production.

Effects of market shares

The results in Sections 6.3.1 and 6.3.2 so far show that the effects of CE strategies vary across technologies, metals, and time. These results are based on medium market share (MMS) pathway. In **Article III**, also a low (LMS) and a high (HMS) market shares pathways are explored in addition to the MMS. Figure 6.5 shows the results for a subset of the eleven technology-specific metals in this thesis that are listed as both critical and strategic raw materials under the European Commission's 2024 Critical Raw Material Act for the LMS, MMS, and HMS pathways analysed in **Article III**. Figure 6.5 shows that, in addition to technologies, metals and time, results also vary across market-share pathway. For example, Figure 6.4e-k shows that for solar power, material intensity reduction produces by far the largest primary demand reductions throughout most of the scenario period. Looking at Figure 6.5a-f, it can be observed that when presenting results across market share pathways, germanium (Figure 6.5a-c) in the LMS pathway, in which the market-share of a-Si diminishes by 2050, is an exception; recycling drives net negative primary demand from 2037 onward (i.e. secondary supply exceed gross demand). Another example is gallium (Figure 6.5d-f), for which substitution remains the second most effective strategy throughout the MMS and HMS pathways but in the LMS pathway it ranks second until 2046, after which recycling yields greater reductions.

Overall, the results show that if the material intensity reductions (narrow strategy) are achieved, by 2050, 19-66% (depending on metal and market-share pathway) of cumulative primary demand could be avoided. For the second narrow strategy (substitution), the reduction varies between 4 and 38% across metals and market-share pathways. The slow strategy (longer design lifespan) achieves lower reductions, in the order of 0.2-5%. In the absence of slow and narrow CE strategies, the close strategy (recycling) results show that if high collection and recycling rates are achieved by 2050 for wind and solar EoL management, depending on market-share pathway 11-13% of the primary REEs used in wind power, 7-37% for germanium and 4-8% for gallium used in solar could be avoided.

Looking at the combined effects of all CE strategies in the composite C strategy in 2050, compared to the baseline, the annual reduction is in the range of 89%–100% and 86%–117% (depending on metals and market-share pathway) in wind and solar, respectively. Annual primary metal demands are eliminated for germanium in 2037 and 2046 in the LMS and MMS pathways respectively, and for dysprosium and terbium in 2050 in the LMS pathway. Therefore, consistent with earlier research [16,45,110,119,121], the results show that adopting less material-intensive sub-technologies as per the LMS pathway substantially lowers metal demand, as reflected in the marked differences across the three market-share pathways.

Overall, the effectiveness of CE strategies in reducing primary demand varies substantially by metal, technology, market-share pathway, and over time. Therefore, no single solution fits all contexts; policymakers and industry could tailor strategy portfolios to specific metals and timing, such as building early recycling capacity for certain metals while prioritizing rapid-effect strategies like material intensity reduction and substitution for others.

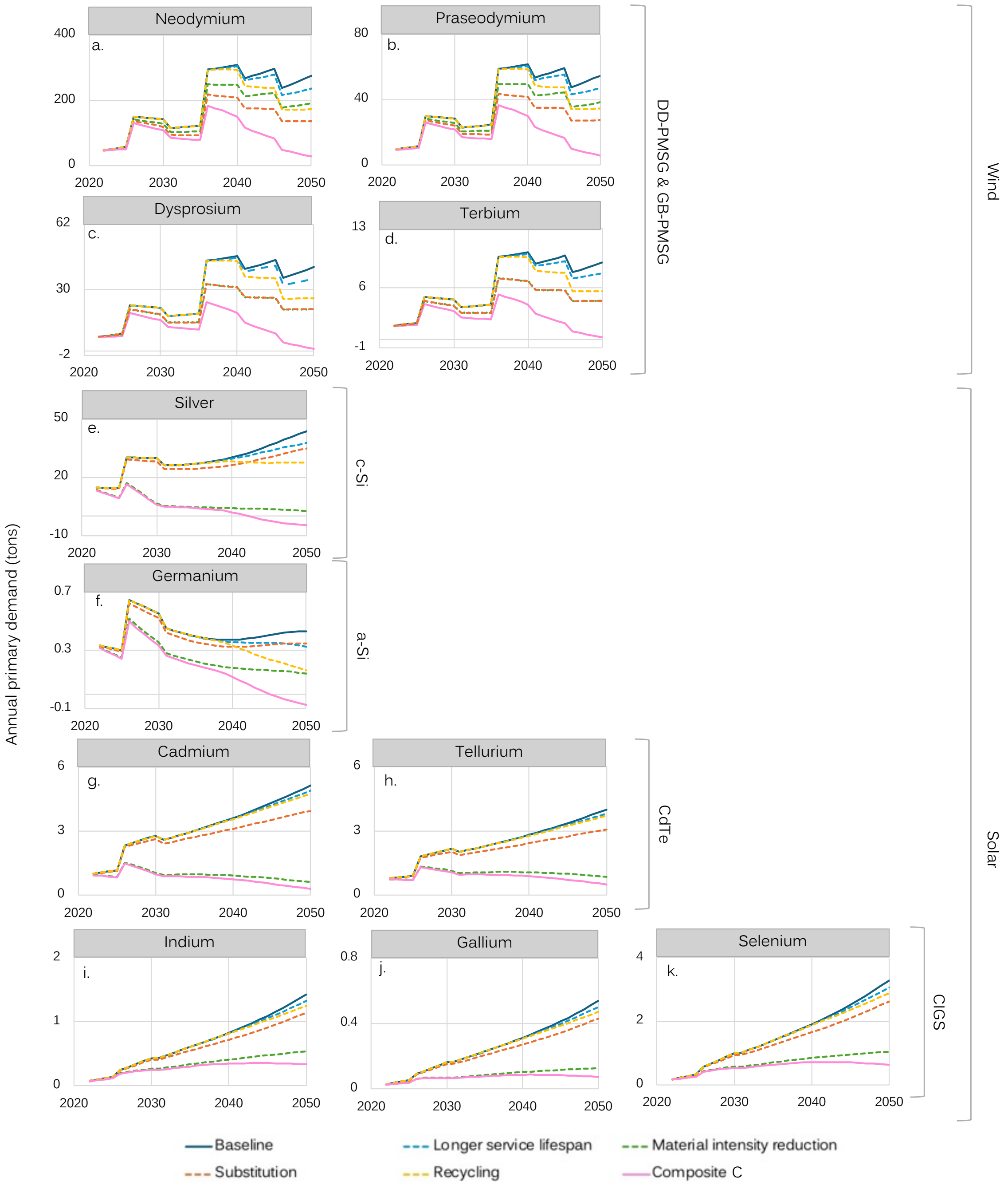


Figure 6.4: Annual primary demand in tons per year per CE strategy and minor metal used for wind (a-d) and solar (e-k) power. Scenario, geography: Renewable Electrification, Sweden. Source: **Articles II** and **III**.

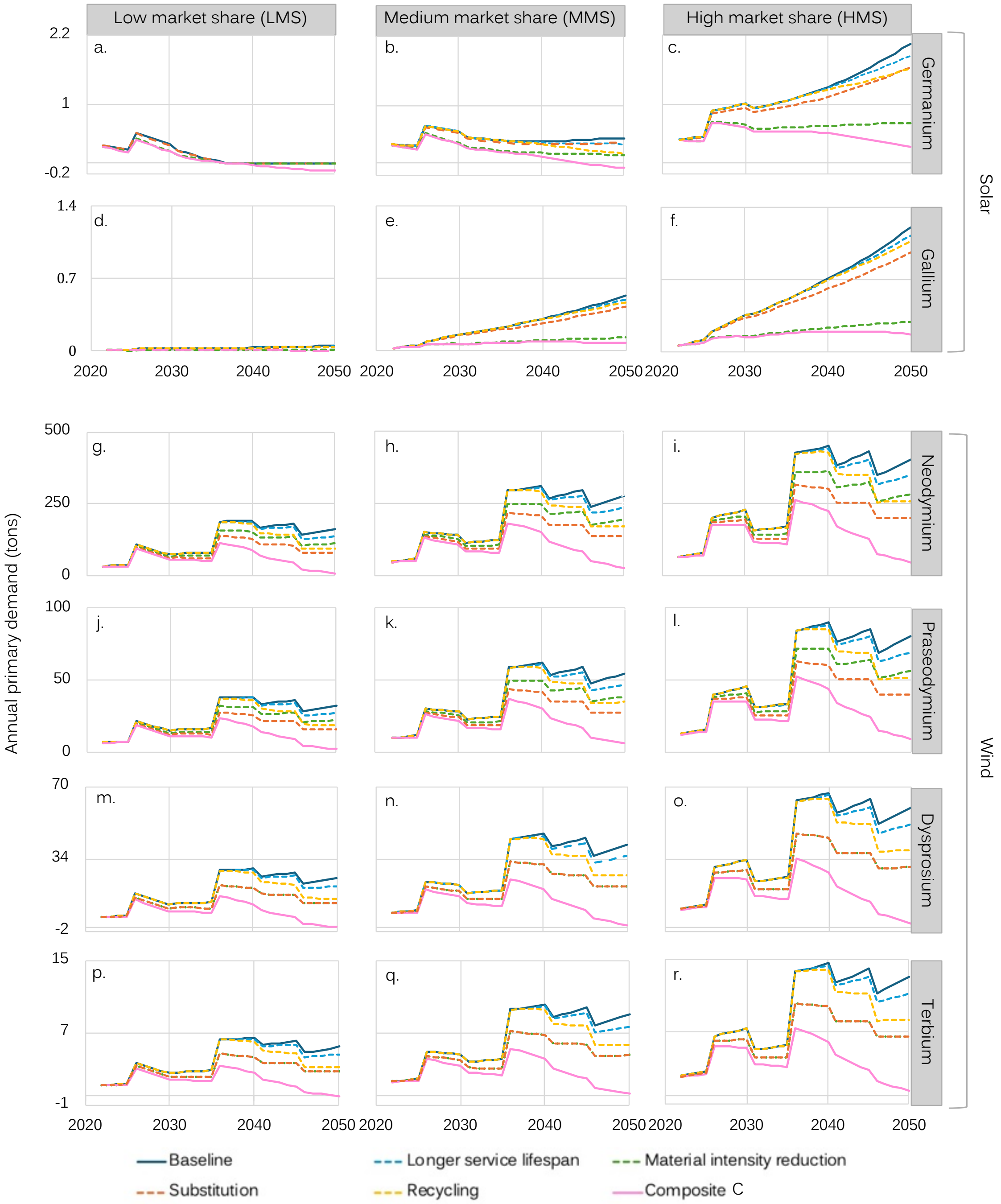


Figure 6.5: Annual primary demand for the metals germanium (a–c), gallium (d–f), neodymium (g–i), praseodymium (j–l), dysprosium (m–o), and terbium (p–r) under three market-share pathways: LMS (a, d, g, j, m, p), MMS (b, e, h, k, n, q) and HMS (c, f, i, l, o, r). LMS and MMS pathways germanium and gallium series are shown in higher resolution in Supplementary Figure S2 of **Article III**. Scenario, geography: Renewable Electrification, Sweden. Source: **Article III**.

6.3.3 Gross demand, primary demand, and secondary supply

Effects of CE strategies on secondary supply

While appended **Articles I** and **II** do not include recycling as a CE strategy and therefore do not provide estimates the quantities of recycled materials (secondary supply), both articles provide estimates of its potential. In **Article I**, the potential secondary supply is estimated using an indicator called the *circularity potential*, which is defined as the outflows divided by the inflows (see Table 2 in **Article I**). In addition to the circularity potential indicator, in **Article I** the inflows and outflows are plotted together to show the physical scale of the flows (see Figure 5 in **Article I**). In **Article II**, the term circularity potential is not used, acknowledging that recycling is not included as a strategy in the study. Instead, the term *demand-supply metal balance* is used, which better represents what is shown, i.e., the difference between the inflows and outflows.

Both approaches make use of the same model results (inflows and outflows), although they use different terminologies and estimation techniques. The first approach (outflows over inflows) has the benefit of having the quantification normalized across the results, which enables direct comparisons between the scenarios and the results for the materials. It lacks the physical unit, and thus an appreciation of the scale, which is provided in a separate figure (see Figure 5 in **Article I**) as "snapshots" in specific years. The second approach (inflows minus outflows) retains the physical unit and provides the values for all the years of the scenario period (see Figure 3 in **Article II**).

In **Article III**, the quantity of the secondary metal supply (recycled metals) that can contribute to fulfil the gross metal demand within the wind and solar power applications, as well as the remaining secondary supply that can cover metal demands in other applications, are estimated.

Figure 6.6 shows the gross demand, primary demand, and secondary supply in tons per metal for the period of 2022–2050, under the composite B and composite C strategies. Composite B includes the join implementation of material intensity reduction, substitution and recycling. For this section the focus is on composite C strategy, which includes all four CE strategies, longer service lifespan, material intensity reduction, substitution, and recycling, spanning therefore the full spectrum of the Slow-Narrow-Close framework on effects on material flows. The focus is also on secondary supply, i.e., the dotted pink lines in Figure 6.6.

For wind power (Figure 6.6a-d), before the 2040s, the secondary supply is an insignificant source of metals. However, by the last 5 years of the scenario period (2046–2050), 56% and 72% of the gross demands for LREEs (Figure 6.6a-b) and HREEs (Figure 6.6c-d) could be supplied from generating capacity that reaches its EoL in that same period. For solar power, the secondary supply before the 2040s is also kept at negligible levels, with the exceptions of cadmium and tellurium, for which recycling is already at high levels nowadays (Figure 6.6g-h). The primary demands for silver and germanium used in the c-Si and a-Si sub-technologies (Figure 6.6e-f) are eliminated from 2043 and 2046 onwards, respectively (as also shown in Figure 6.4e-f). The secondary supply levels from solar applications from these years onward are sufficient to meet the entire gross demand. For both metals, there is a remaining supply for other applications. For silver, the remaining secondary supply available for other applications exceeds the secondary supply needed to fulfil the demand within the system in 2046. By 2050, the former is 2.5-times larger than the latter. For germanium, the remaining supply for other applications remains lower than the secondary supply needed within the system. For cadmium and tellurium used in the CdTe sub-technology, the secondary supply within the system can cover 56% and 42% of the gross demands, respectively, in the period of 2046–2050. For the remaining metals (used in the CIGS sub-technology), the secondary supply has a substantially weaker potential, reaching 13%, 18%, and 15% of the gross metal demands in 2046–2050 metal demand for indium, gallium, and selenium, respectively.

Overall, the composite C strategy shows that towards 2050, the CE strategies combined can substantially increase the secondary supply potential towards the end of the scenario period. While the findings show that by 2050 the secondary supply can cover more than half of the gross metal demand for all the REEs and for silver, germanium, and cadmium, the results are similar to those reported in previous studies, pointing to the limited potential of recycling in the short-term [43,101,122,123]. In the near future, recycling can only lead to small reductions in primary metal demand, since EoL outflows are limited in the early phase of the transition. Nevertheless, for some metals (silver, germanium, dysprosium and terbium) primary demand is almost or entirely eliminated, even leaving surplus supply for other applications (in silver and germanium). This underscores the importance of initiating and scaling recycling efforts, especially for these metals, to reduce reliance on primary sources [22].

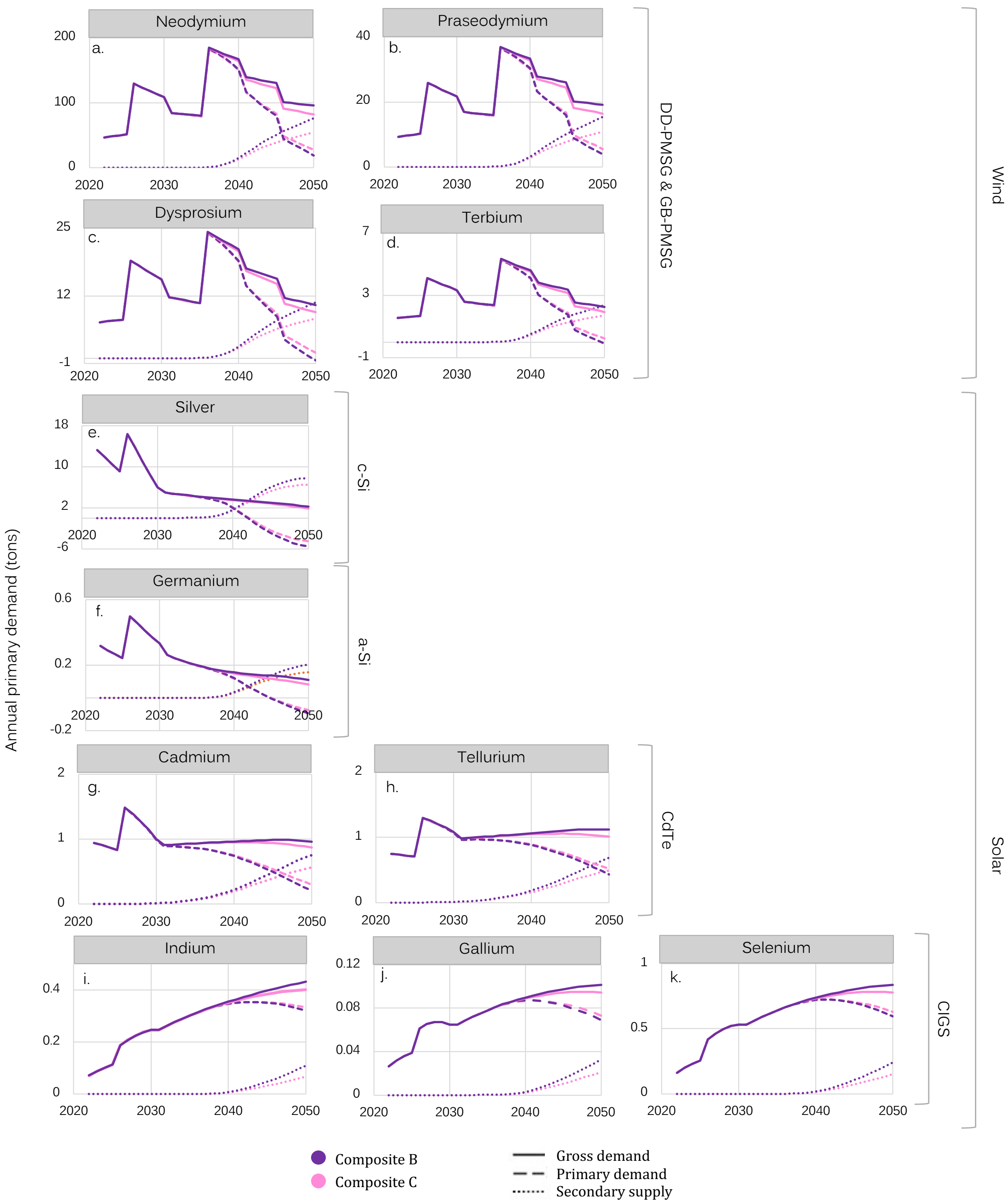


Figure 6.6: Gross demand (solid lines), primary demand (dashed lines) and secondary supply (dotted lines) in tons per year for each metal for wind (a-d) and solar (e-k) power in the composite B and composite C strategies. Scenario, geography: Renewable Electrification, Sweden. Source: **Articles II** and **III**.

Trade-off between gross and primary demand

This section synthesizes findings related to the trade-offs identified in **Article I**, further explored in **Article II** and examined in a more comprehensive manner in **Article III**.

The focus now is on both composite B and C in Figure 6.6, as well as the dynamics between the primary and gross demand. As can be seen in Figure 6.6, towards the end of the scenario period, primary demand under the composite B strategy, which combines the material intensity reduction, substitution and recycling, becomes lower than that of the composite C strategy, which includes in addition the longer design lifespan. In fact, the primary demand does not follow a consistent trend throughout the scenario period, but this is hardly visible in Figure 6.6 because the differences are relatively small. Figure 6.7 shows the difference ($\Delta_{\text{Primary demand}}$) in primary demand between composite C and composite B strategies over the scenario period for a subset of the metals analysed in the thesis (those listed as both critical and strategic raw materials under the European Commission's 2024 Critical Raw Materials Act), which is calculated as follows:

$$\Delta_{\text{Primary demand}} = \text{Primary demand}_{\text{composite C}} - \text{Primary demand}_{\text{composite B}}$$

Negative values indicate that the primary demand of the composite C strategy is lower than that of composite B strategy and positive values indicate the opposite. As can be seen, for the first part of the scenario period, primary demand of the composite C strategy is slightly lower than that of composite B strategy but then, as EoL capacity outflows increase and recycling rates are increasing in the later stage of the transition, this reverses and becomes comparatively much higher. Cumulatively this results in having higher primary demand in the composite C strategy for the scenario period as a whole. Overall, this indicates that, if the goal is solely to reduce total primary demand during the scenario period, prioritizing the narrow and close strategies without implementing the slow strategies may be preferred.

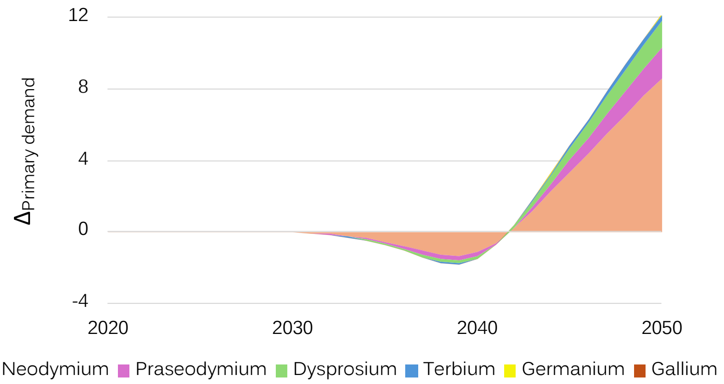


Figure 6.7: Difference (Δ) in primary demand between composite C and composite B strategies over the scenario period. Primary demand is lower in the composite C until around 2042, after which the trend reverses. Note: Time series for germanium and gallium follow the same pattern as neodymium, praseodymium, dysprosium, and terbium but are not visible due to their smaller scale. Although presented for the MMS pathway, similar trends occur across all three market-share pathways. Scenario, geography: Renewable Electrification, Sweden. Source: **Article III**.

Gross demand, as indicated by the solid lines, in the composite C strategy is consistently lower than the gross demand in the composite B strategy over the scenario period. Therefore, the composite C strategy yields lower gross demand than in the composite B strategy. But this reduction in gross demand is enabled by a higher cumulative primary demand (and lower secondary supply).

This dynamic is due to how different CE strategies affect material flows. Longer service lifespan (the slow strategy) delay technology decommissioning, which postpones both the installation of new technologies, and thus metal inflows, and the generation of scrap metals (outflows) available for recycling. Narrow strategies reduce the material intensity of new technologies, leading to an immediate reduction in inflows required for new installations and a gradual reduction in outflows, as technologies with lower material intensity reach EoL. The combination of slow and narrow strategies reduces both inflows and outflows compared to narrow strategies alone; however, outflows are reduced to a greater extent than inflows. This is demonstrated in **Articles I** and **II** through the lower outflow to inflow ratio or their larger difference (demand-supply balance) respectively. This occurs because, in any given year, outflows depend on the capacity and material intensity of technologies installed at the start of their lifespans, while inflows (gross demand) are based on the capacity and improved, lower material intensities of newer technologies. In **Article III** which includes recycling, this trend can be observed in terms of primary and gross demand. In particular, secondary supply results from outflows multiplied by collection and recycling rates, which start at zero but increase rapidly after 2035, becoming significant toward the late 2030s (see Supplementary Figure S1 in **Article III**). Since gross demand equals primary demand plus secondary supply, and secondary supply decreases more sharply than gross demand, primary demand must increase slightly to compensate, resulting in greater reliance on primary production.

Therefore, during the scenario period, using the slow strategy (longer design lifespan) in combination with the narrow and close strategies creates a trade-off between the objective of reducing gross demand on the one hand, and reducing the primary demand on the other hand. Gross demand reduction addresses the urgent, system-scale need to deploy renewable technologies quickly to meet decarbonization targets, whereas primary demand reduction avoids larger supply-chain environmental and social impacts, often borne disproportionately by low-income or Indigenous communities [124,125]. Thus, the trade-off reflects a tension between speed and scale of deployment and the equity and environmental harms of primary sourcing. This trade-off is observed during the transition period with large-scale deployment of renewable technologies. Beyond the scenario period, the effects of both longer design lifespan and recycling are expected to increase, and at the same time, the deployment of renewable technologies may slow down, following the achievement of decarbonization target. This would have an effect on the trade-off observed.

6.3.4 Supply requirements

Previous articles in this thesis examined material demand from different perspectives. **Articles I** and **II** focused on inflows, that is, gross demand. **Article III** expanded the analysis to include primary demand alongside gross demand. Building on this, **Article IV** accounts for supply chain losses, particularly during production, fabrication, and manufacturing, and examines the required annual material production and associated reserves needed to support the large-scale deployment of wind technologies over the scenario period. This extends the assessment of CE strategy effects from demand requirements to supply requirements. Given the central role of these metals in decarbonisation technologies beyond wind turbines, this analysis could provide insight into broader material supply pressures beyond the specific technologies considered.

Figure 6.8 presents the required annual production of REEs from 2022 to 2050 under the different CE strategies in the EU Decarbonising Energy scenario. Figure 6.9 shows the corresponding required reserves by 2050.

Annual production

Across all REEs, extending service lifespan shows the smallest reduction potential over the scenario period (Figure 6.8). For LREEs (neodymium and praseodymium), substitution has the strongest effect in reducing production requirements. Recycling initially has a limited effect, followed by material intensity reduction, which contributes moderately. Over time, however, the effect of recycling increases substantially, surpassing material intensity reduction around 2039 and approaching substitution by 2050. For HREEs (dysprosium and terbium), substitution and material intensity reduction show similarly strong effects. Recycling has a smaller but steadily growing effect, becoming comparable to the other strategies after 2045. The composite C strategy shows that combining all strategies leads to substantial reductions across all REEs, reducing production requirements for LREEs to near zero by 2050 and eliminating requirements for HREEs from 2047 onward.

Overall, the narrow strategies, substitution and material intensity reduction emerge as the most effective strategies in the short to medium term, while the close strategy (recycling) becomes increasingly important toward 2050.

Reserves

Turning to material reserves (Figure 6.9), longer service lifespan reduces reserve requirements by about 6% relative to the baseline across all REEs. Substitution leads to a substantially larger reduction, lowering reserve requirements by around 29%. Material intensity reduction also yields notable reduction, leading to a 29% reduction for HREEs and by 17% for LREEs. Recycling reduces reserve requirements by 21% across all REEs. The combined strategy produces the largest effect, reducing required reserves by 57% to 64% across metals.

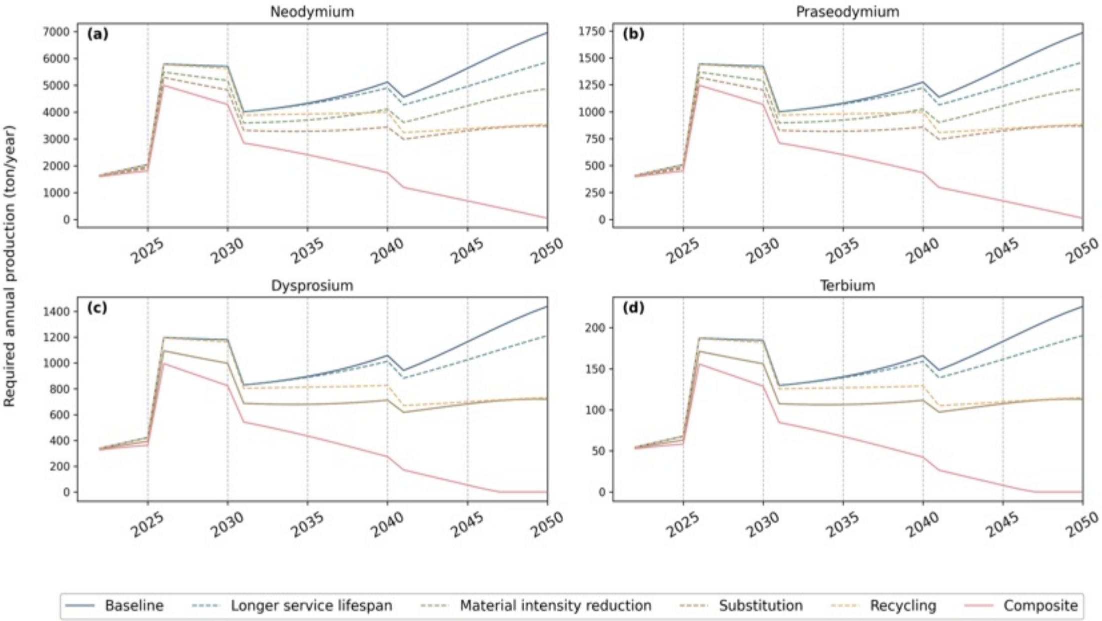


Figure 6.8: Required annual production levels of neodymium (a), praseodymium (b), dysprosium (c), and terbium (d) under the baseline and CE strategies for wind power deployment. Note that the required annual production under metal intensity reduction and substitution strategies are identical for dysprosium and terbium. Scenario, geography: Decarbonising Energy, EU. Source: Article IV.

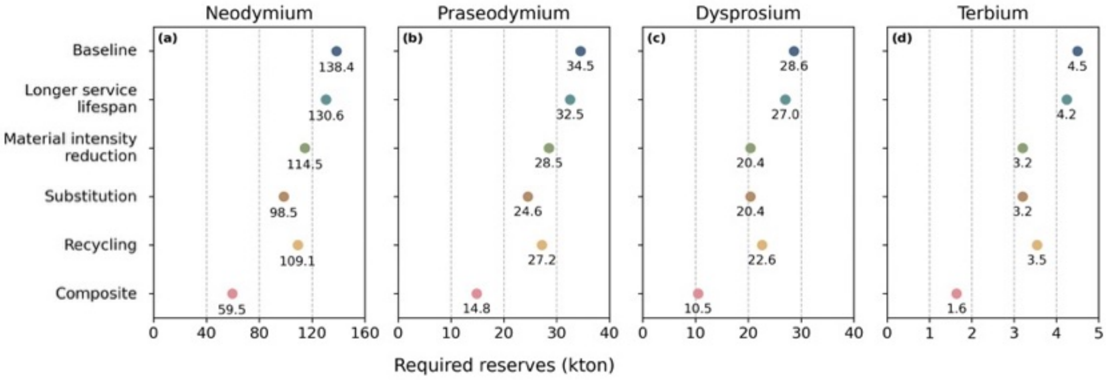


Figure 6.9: Required reserves by 2050 for neodymium (a), praseodymium (b), dysprosium (c), and terbium (d) under the baseline and CE strategies for wind power deployment. Scenario, geography: Decarbonising Energy, EU. Source: **Article IV**.

6.4 Addressing *RQ2*

This section directly addresses *RQ2* which is examined in this chapter.

RQ2: How do individual CE strategies affect the demand for materials and the supply requirements for wind and solar technologies, how do their effects compare in terms of magnitude and timing, and what combined effects and trade-offs arise from their joint implementation during the energy transition?

The answer to this research question is structured in two parts. First, a short section addresses the effects of CE strategies on demand for structural materials, which were covered in **Article I**, followed by a section on technology-specific materials, which is more extensive and covers the work conducted across all articles appended to the thesis.

6.4.1 Structural materials

For the structural materials covered in this thesis, namely steel and concrete, the results indicate that the large-scale deployment of wind power leads to substantial increases in material inflows. In the absence of CE strategies, demand grows significantly as capacity expands, making the share of steel and concrete requirements in total national use of 2020 increasingly substantial. The CE strategies analysed, longer service lifespan and material intensity reduction, contribute to moderating this growth; however, their overall reduction potential remains relatively modest compared to that observed for technology-specific materials.

At the same time, material outflows from decommissioned infrastructure increase considerably over time. While these outflows remain lower than inflows during the transition period, they indicate a growing potential for secondary supply in the longer term, contingent on the development of appropriate recovery and recycling systems.

6.4.2 Technology-specific materials

The results of this thesis show that CE strategies have substantial but highly distinct effects on material demand and supply requirements in wind and solar technologies. Their effects vary across technologies, metals, market share pathways, and over time, indicating that no single strategy performs best across all contexts. Nevertheless, several consistent patterns emerge regarding their magnitude, timing, combined effects, and associated trade-offs.

In terms of magnitude, strategies that narrow material flows, namely material intensity reduction and substitution, demonstrate the greatest potential for reducing metal demand and associated supply requirements during the energy transition. Their importance differs across technologies. For solar power, material intensity reduction consistently has the strongest reduction potential, while for wind power, substitution emerges as particularly influential for REEs.

In addition to differences in magnitude, CE strategies also differ substantially in their effects over time. Material intensity reduction and substitution that narrow material flows have an immediate effect, as they directly influence the material content in newly installed capacity, making them particularly relevant in the early and middle stages of the energy transition when deployment rates are highest. In contrast, the effects of recycling and longer service lifespan are more delayed. Recycling depends on the availability of EoL material flows, which remain limited during the initial stages of the energy transition. Similarly, longer service lifespan affects material flows with a lag based on the lifespan of technologies, reducing replacement demand and shifting inflows and outflows over time rather than lowering demand. As a result, narrow strategies studied have effects in the short term, whereas the close strategy becomes increasingly important toward the end of the scenario period, while the slow strategy is expected to have greater effect beyond it. This temporal differentiation highlights that CE strategies operate on different timescales and should be considered accordingly.

When implemented jointly, CE strategies can reduce cumulative primary metal demand and associated required reserves by more than half for all metals studied over the scenario period. Similarly, their combined implementation substantially reduces annual primary demand and annual required production and even eliminates them for some metals toward the end of the scenario period. Overall, these results demonstrate that the joint implementation of the CE strategies studied in this thesis spanning the Slow–Narrow–Close exhibit strong reduction potential.

However, despite these substantial reductions, primary demand and required supply for most metals persists throughout the scenario period. This indicates that these CE strategies alone are not sufficient to satisfy the increasing material demand associated with large-scale deployment of wind and solar technologies. In other words, even under ambitious CE implementation, additional primary and/or secondary supply remain necessary. This implies that meeting decarbonization targets, as currently modelled in decarbonization scenarios, will require an expansion of metal production alongside the implementation of CE strategies.

A key insight arising from the combined implementation of CE strategies is the existence of a trade-off between reducing gross demand and reducing primary demand. During the scenario period, combining the slow strategy of longer service lifespan with the narrow and close strategies studied results in lower cumulative gross material demand, but higher cumulative primary demand compared to the narrow and close strategies alone. This trade-off reflects a broader tension between different sustainability objectives. Reducing gross demand supports the urgent need to deploy renewable technologies at scale to meet decarbonization targets, while reducing primary demand mitigates the environmental and social impacts of extraction and processing, which are often disproportionately borne by low-income or Indigenous communities. The trade-off therefore highlights a tension between the speed and scale of the energy transition and the equity and environmental implications of material sourcing. Importantly, this trade-off is specific to the transition period, beyond which as deployment is expected to stabilise and material outflows increase, the combined benefits of longer service lifespan and recycling are expected to strengthen, potentially altering this relationship over time.

CHAPTER 7

Equitable allocation

This chapter presents and discusses the results obtained in **Article IV**, which addresses *RQ3*.

Article III operationalises the equality principle using a per-capita allocation as a benchmark for production capacity. This approach is used to assess the ability of extraction and refining industries to supply the metals studied and to highlight the scale of expansion needed in primary and/or secondary supply. The results show that an equal-per-capita share of annual global production is not sufficient to meet primary demand for most metals throughout the scenario period under any CE strategy. Additionally, it shows that production capacity would need to expand more strongly for REEs in wind power than for the minor metals used in solar power.

In **Article III**, equity considerations were addressed indirectly through the trade-off between reducing gross demand and reducing primary demand. Lower gross demand supports rapid renewable energy deployment, while lower primary demand reduces environmental and social burdens associated with extraction and processing, which are often disproportionately borne by low income and Indigenous communities [124,125]. This trade-off highlights a tension between the scale and speed of the energy transition and the distribution of its impacts.

Article IV explicitly analyses equity in the allocation of REEs, as described in the methodological framework presented in Section 4.1.2. This chapter synthesises these results by examining whether required production and reserves under different CE strategies, are compatible with equitable shares of global production and reserves according to the equality, need, and capability principles.

7.1 Annual production

Figure 7.1 presents the required annual production for neodymium, praseodymium, dysprosium, and terbium between 2022 and 2050 under the CE strategies. For each metal, the equality, need, and capability allocation ranges are shown, spanning from the constant production case (lower bound) to the dynamic production case (upper bound).

When evaluated against equitable allocation principles, required annual production places sustained pressure on global supply systems across all four REEs (Figure 7.1). Five main patterns emerge.

First, required annual production exceeds equitable allocation ranges most strongly in the early phase of the scenario period across equity principles. This pattern is driven by the rapid scale-up of wind power capacity assumed under the Decarbonizing Energy scenario. At the same time, CE strategies are not yet realised at their full potential in the initial years of the scenario. This is particularly evident for the narrow strategies which, as demonstrated in Chapter 6, *Material demand*, exhibit the greatest reduction potential over the scenario period. As a consequence, even when allowing for continued growth in global annual production, equality, need, and capability allocation benchmarks are substantially exceeded during this phase.

Second, for all REEs, the composite C strategy ultimately reduces required primary production to near-zero or zero toward the end of the scenario horizon, showing that while for most of the transition period CE strategies are not sufficient to bring required production within equitable allocation bounds, their implementation is crucial to achieve that toward the end of the energy transition period.

Third, the comparison across equity principles provides several important insights. The equality principle, implemented here as an equal-per-capita allocation, consistently yields the least stringent benchmarks. By contrast, the need and capability principles impose substantially tighter constraints, reflecting differences in development needs and economic capacity. The EU’s projected demand exceeds these more stringent benchmarks for several metals, indicating that assessments based solely on equal-per-capita allocations, as is common in the current literature, may underestimate the degree of inequity embedded in prevailing transition pathways.

Fourth, the level of CE intervention is important for the extent to which annual required production becomes compatible with an equitable share of globally available annual production. CE strategies implemented individually are generally insufficient to achieve sustained compatibility across all allocation principles. In contrast, the composite C strategy falls below all the allocation ranges of all three principles, albeit only towards the end of the scenario period, reflecting the need for implementing CE strategies across the Slow-Narrow-Close framework.

Fifth, there are considerable differences between LREEs and HREEs. LREEs, neodymium and praseodymium, exhibit broadly similar dynamics, with required annual production approaching or falling within allocation ranges earlier than is the case for HREEs, dysprosium and terbium. In fact, for the HREEs, required annual production under the baseline and all individual CE strategies remains well above equality, need, and capability allocation benchmarks for most or all of the scenario period. This divergence between LREEs and HREEs persists despite faster assumed declines in material intensity for HREEs relative to LREEs (see Table 4.2 in Chapter 4, *Methodology*). The underlying driver is the substantially larger gap between current production levels and modelled future requirements for the HREEs, which results in sustained pressure relative to all allocation benchmarks. This underscores that CE strategy implementation alone is insufficient to offset the large gap between current production levels and projected demand.

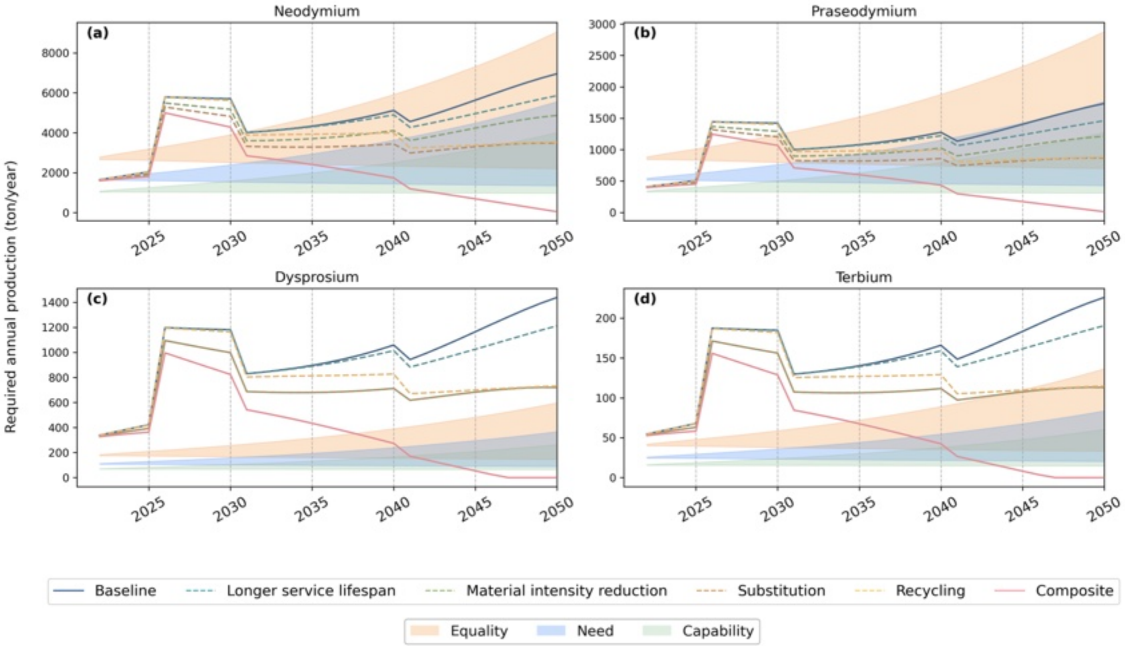


Figure 7.1: Required annual production levels of neodymium (a), praseodymium (b), dysprosium (c), and terbium (d) under the baseline and CE strategies for wind power deployment. For each metal, all three allocation ranges are shown, comprising equality (orange), need (blue), and capability (green). Each range spans from the constant (lower bound) to the dynamic (upper bound) annual production value. Note that the required annual production under metal intensity reduction and substitution strategies are identical for dysprosium and terbium. Scenario, geography: Decarbonising Energy, EU. Source: **Article IV**.

7.2 Reserves

Figure 7.2 shows the required reserves by 2050 for the four REEs studied, under the CE strategies and equity principles. As in Figure 7.1, for each metal, the equality, need, and capability allocation ranges are shown, spanning from the constant reserve case (lower bound) to the dynamic reserve case (upper bound).

Compared to required annual production, required reserves by 2050 present a more differentiated picture across LREEs and HREEs, although equity constraints remain particularly salient for HREEs (Figure 7.2). Required reserves capture cumulative material demand and therefore reflect longer-term material availability rather than shorter-term production capacity.

For the LREEs neodymium and praseodymium, required reserves fall within all three allocation ranges under both the baseline and all CE strategies considered. No CE strategy approaches the lower bounds of equality, need, or capability allocations. This indicates that, from a reserve's perspective, these metals do not constitute binding constraints for wind power deployment under the Decarbonizing Energy scenario, leaving space for their use in other applications from an equity perspective. Consequently, equity challenges associated with neodymium and praseodymium use in wind power arise primarily from production dynamics rather than long-term material availability. However, this finding should be interpreted in the context of broader demand. The results presented here consider wind power only, while other technologies, including electric vehicles, also rely on these REEs. The extent to which these materials are required across competing applications is not quantified in this analysis.

The situation for the HREEs dysprosium and terbium is markedly different. For dysprosium, required reserves exceed all allocation ranges under the baseline and all individual CE strategies, and remain above need and capability benchmarks even under the composite C strategy. This is driven by higher losses along the supply chain, including those associated with production, fabrication, and manufacturing (see Supplementary Table S1 in **Article IV**), combined with rapidly declining available reserves. These results suggest that achieving equitable allocation for dysprosium would require action beyond the full implementation of CE strategies within wind power.

Terbium occupies an intermediate position to those described above. Under the baseline and all individual CE strategies, required reserves exceed the need- and capability-based allocations, although material intensity reduction, substitution, and recycling reduce requirements below the equality-based allocation. In contrast to dysprosium, the composite C strategy is sufficient to bring required reserves within all three allocation ranges, albeit only marginally under capability-based benchmarks. This indicates that, for terbium, long-term equity constraints within wind power could be alleviated through sufficiently ambitious CE strategies. However, given that wind power alone already imposes significant pressure on terbium availability, and that terbium is also required for other key decarbonisation technologies, these results still point to a broader system-level constraint.

Overall, the findings indicate that the EU decarbonisation scenario places substantial pressure on the four REEs considered, particularly dysprosium and terbium. This is especially important given that all four metals are critical inputs for PM motors used in electric vehicles, as well as in other applications. Since this analysis focuses exclusively on wind power, the allocation benchmarks are already challenged by a single technology. Including demand from electric vehicles and other sectors would further increase both production and reserve requirements, underscoring the urgency of implementing demand reduction and the adoption of CE strategies across multiple sectors.

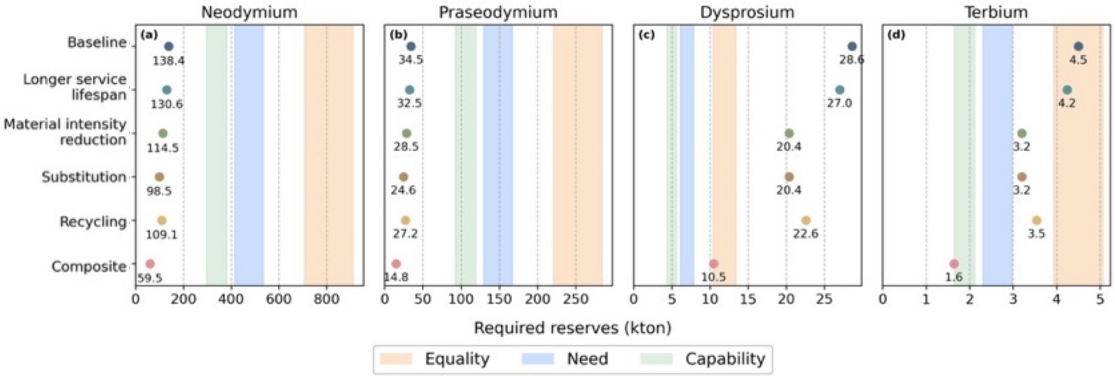


Figure 7.2: Required reserves by 2050 for neodymium (a), praseodymium (b), dysprosium (c), and terbium (d) under the baseline and CE strategies for wind power deployment. Each subplot includes all three allocation ranges, depicted as equality (orange), need (blue), and capability (green), for comparison. Each range spans from the constant (lower bound) to the dynamic (upper bound) reserve value. Scenario, geography: Decarbonising Energy, EU. Source: **Article IV**.

7.3 Addressing *RQ3*

This section directly addresses *RQ3* which is examined in this chapter.

RQ3: To what extent is the required material supply for wind power during the energy transition compatible with selected equity principles, and how can CE strategies improve this compatibility?

The results show that the REE supply required for wind power under the EU decarbonisation scenario is only partially compatible with the equity principles considered, and remains largely incompatible for certain metals, even when CE strategies are implemented. Across the REEs analysed, required annual production frequently exceeds equitable allocation ranges, particularly during the early and middle phases of the transition. This reflects the rapid scale-up of wind power capacity, which drives high short-term demand for primary material supply, outpacing even growing production levels and the mitigating effects of CE strategies.

Compatibility with equity principles improves over time, but remains uneven across metals. For LREEs (neodymium and praseodymium), individual CE strategies gradually bring required annual production closer to or within allocation ranges toward the end of the scenario period. In contrast, for HREEs (dysprosium and terbium), required production under both the baseline and individual CE strategies remains above equality, need, and capability benchmarks for most or all of the transition period. This divergence highlights a structural constraint: the gap between current production levels and projected demand is substantially larger for HREEs, limiting the effectiveness of CE strategies.

CE strategies play a clear but limited role in improving compatibility with these equity benchmarks. Individually, CE strategies are generally insufficient to bring required production within equitable allocation ranges. Their effects also differ over time: material intensity reduction and substitution provide earlier reductions in demand, while recycling and longer service lifespan have delayed effects linked to stock turnover dynamics. Only the combined implementation of CE strategies across the Slow–Narrow–Close framework results in required production to be compatible with all three equity allocations, and even then, compatibility is achieved primarily in the later stages of the transition.

The analysis of required reserves provides additional insight into longer-term equity considerations. For LREEs, cumulative demand remains within allocation ranges across scenarios, indicating that long-term availability is less likely to constitute a binding constraint from an equity perspective. However, for HREEs, particularly dysprosium, required reserves exceed equitable allocations even under the joint implementation of CE strategies. This suggests that, for these metals, equity challenges are not limited to short-term production capacity but extend to structural limitations in resource availability.

The results should be understood within the scope of the analysis, which focuses exclusively on wind power. Since the same REEs are critical inputs for other key technologies, such as electric vehicles, the pressure identified here represents only a partial view of total demand. Incorporating these additional demands would further exacerbate the misalignment with equity principles.

The comparison across allocation principles further reveals that compatibility is sensitive to how equity is defined. The equality principle, operationalised as equal-per-capita allocation, yields the least stringent benchmarks and therefore suggests a higher level of perceived compatibility. In contrast, the need and capability principles impose substantially tighter constraints, under which the EU's projected demand exceeds equitable allocations more frequently and to a greater extent. This indicates that assessments based solely on per-capita approaches may underestimate the degree of inequity associated with material demand for current decarbonization scenarios. This is consistent with interpretations of equality that emphasize equal sacrifice rather than equal entitlements, under which per-capita approaches may be inequitable if they ignore morally relevant differences in countries' needs and capabilities.

An alternative perspective places greater emphasis on the urgency of the climate crisis, prioritising the rapid deployment of low-carbon energy over considerations of equitable metal allocation. From this viewpoint, the focus shifts from distributing materials according to predefined equity principles toward using available resources in a way that maximises emissions reductions. While this risks issues of carbon tunnel vision, it raises questions about the applicability of equity benchmarks, particularly in a global economy where countries differ in production roles and energy demand structures. In such contexts, ensuring universal access to sufficient energy for decent living standards (DLS) may serve as a starting point on which more specific allocations can be developed.

Overall, the analysis demonstrates that compatibility with equitable allocation for the three selected principles cannot be achieved through the CE strategies studied alone. Even with full CE implementation, the EU's wind power deployment places disproportionate pressure on globally available REEs, particularly when assessed under need- and capability-based principles. This implies that achieving an equitable energy transition, as defined in this analysis, requires broader systemic adjustments. These may include implementing additional CE strategies across sectors to reduce material demand, reducing energy demand across sectors, and potentially reconfiguring material-intensive growth scenarios.

Beyond the empirical findings, this thesis also contributes an analytical framework for assessing the equity of metal allocation in energy transitions. By operationalising the principles of equality, need, and capability, the framework translates normative concepts into quantitative allocation benchmarks that can be directly compared with future material demand. This enables a structured and transparent assessment of how differing equity principles shape conclusions about the compatibility of energy transitions with global resource constraints.

The framework is designed to be transferable. The distinctions drawn between demand estimation, the derivation of production and reserve requirements, and the construction of equity-based benchmarks allows it to be applied to other materials, technologies, spatial scales, and scenario assumptions. While demonstrated here for REEs in wind power, the approach can support broader comparative analyses of equity implications across energy systems.

At the same time, the framework highlights the normative and empirical assumptions embedded in equity-based assessments. The reliance on proxies to represent principles introduces simplifications and uncertainties, meaning that the results should not be interpreted as definitive measures of equity. Rather, the framework provides a tool for transparent and comparative analysis of how alternative equity perspectives influence the evaluation of material demand in the energy transition.

CHAPTER 8

Discussion

This chapter discusses the generalizability of the results, provides a reflection of their relevance for stakeholders, discusses the study's limitations, and suggest avenues for future work.

8.1 Generalizability of results

The patterns observed in this thesis regarding the timing of CE strategy effects are not limited to the specific strategies analysed but can be understood more broadly within the Slow–Narrow–Close framework. In particular, the distinction between strategies that act directly on material inflows and those that operate through stock dynamics can be extended to other CE strategies beyond those explicitly modelled. For example, repair, remanufacturing, lifetime extension and other strategies that similarly act by slowing material flows and are therefore likely to exhibit delayed effects, as their benefits materialise through reduced replacement demand over time. Conversely, strategies that reduce material inputs per unit of service (narrow strategies), such as design optimisation or alternative system configurations, can be expected to deliver more immediate reductions, consistent with the effects observed for material intensity reduction and substitution.

These temporal patterns are also likely to be generalisable across other technologies beyond those considered in this thesis. In particular, the finding that recycling tends to have a delayed, long-term effect, driven by the availability of EoL material flows, reflects a structural characteristic of stock-based systems rather than a technology-specific outcome.

While the magnitude of these effects will depend on the specific technology, material, and context, the general temporal differentiation identified in this thesis is likely to apply more widely. This suggests that the insights derived here can inform broader assessments of CE strategies, highlighting the importance of considering both their timing and interaction effects when evaluating their role in reducing material demand and supply requirements in the energy transition.

8.2 Implications for stakeholders

The findings of this thesis have implications for a broad set of stakeholders involved in the energy transition, including policymakers, industry actors across wind and solar supply chains, and the research community.

8.2.1 Implications for policy and governance

The results reinforce the growing recognition that material demand and availability are relevant considerations in the energy transition. Under large-scale deployment scenarios for wind and solar technologies, which are widely considered the most plausible pathway, demand for materials increases substantially, even when CE strategies are widely implemented. In this context, existing policy initiatives, such as those targeting technology design, EoL management, and supply security, address key aspects of this increasing demand. The findings point to the value of further integrating and expanding these efforts, particularly through the implementation of CE strategies across the lifecycle of wind and solar technologies. They also highlight the relevance of complementary dimensions beyond those directly analysed, including reducing energy demand, which can lower near-term pressures on material systems, and strengthening primary supply governance to ensure that continued reliance on extraction is accompanied by robust environmental and social standards.

The results show that the effectiveness of CE strategies varies significantly across materials, technologies, market shares, and time. This suggests that policy mixes, rather than single strategies, are likely to be more effective. Such mixes could evolve over time, for example by prioritising design-related measures in the short-term while supporting the development of recycling systems that become more relevant as technologies reach EoL. The results also highlight a trade-off that arises when CE strategies across the Slow–Narrow–Close framework are jointly implemented during the transition. This suggests the importance to consider how such trade-offs evolve over time, in order to better sequence and combine policy measures and support the prioritisation of strategies at different stages of the transition.

A further implication concerns the distributional aspects of material use. The analysis indicates that, under certain assumptions, current decarbonisation pathways may imply a relatively large share of globally available metals being allocated to high-demand regions such as the EU. Since metals are under national sovereignty and global governance mechanisms remain limited, addressing such imbalances is inherently complex. Equity considerations are important to be addressed. This could be done at difference scales, such as through regional policies shaping demand and sourcing practices, regulatory frameworks governing supply chains and international cooperation.

Within this context, high-demand regions may play a particularly important role by advancing CE, reducing energy demand, and promoting responsible sourcing, thereby easing pressure on global supply systems. Making equity considerations in material use more visible within international climate and resource policy discussions could support more informed and transparent decision-making, even if formal global allocation mechanisms remain unlikely.

8.2.2 Implications for industry

For industry actors, the findings suggest that material-related risks and opportunities are likely to become more pronounced over time. While primary material supply under the energy transition as currently planned is expected to remain necessary, even under ambitious CE implementation, increasing demand may lead to greater exposure to price volatility, supply disruptions, and regulatory pressures.

At the same time, CE strategies provide opportunities to mitigate these risks. Their effectiveness varies across materials, technologies, market shares, and time horizons. This highlights the importance of:

- combining multiple strategies, rather than relying on single approaches
- adapting strategies to specific positions within the value chain, recognising that different actors, such as manufacturers, energy developers, and recycling firms, have distinct roles and capabilities, while also encouraging supply chain collaboration
- and anticipating temporal dynamics, such as the delayed availability of secondary materials

The findings also highlight trade-offs that need to be managed. Strategies that slow material flows can reduce overall demand during the transition but may delay the availability of recyclable materials, affecting secondary supply. Understanding these interactions can support more informed investment and planning decisions, particularly in recycling.

Recycling becomes increasingly effective toward the later stages of the energy transition, a finding that aligns with previous research [43,101,122,123]. Establishing and improving recycling systems is therefore important to realise the long-term potential of secondary supply, especially for technology-specific materials that currently exhibit low recovery rates and face technical and economic barriers. Despite limited established systems, some of these metals show high theoretical recycling efficiencies [126–128]. However, separation and purification remain technically demanding, and economic viability depends on sufficient EoL volumes [129]. Stockpiling EoL materials has been suggested as a potential strategy until recycling becomes economically viable [100].

Overall, the findings can support and inform existing industry initiatives by providing a more integrated understanding of how different strategies interact over time and across materials.

8.2.3 Implications for research

The findings point to several directions for future research and innovation, building on ongoing work in material substitution, recycling, and energy and material system modelling. A key priority is the development of substitutes for materials, particularly REEs such as dysprosium and terbium. Advancing substitution options, including REE-free technologies, could significantly reduce reliance on vulnerable supply chains. In parallel, further efforts are needed to establish and improve recycling systems, especially for technology-specific materials. The results also highlight the need to advance modelling approaches that more effectively integrate energy and material system dynamics, including their interactions over time, in line with existing research [31].

This thesis contributes a framework for assessing equitable material allocation, providing an initial approach for analysing how different transition scenarios relate to global equity considerations. Research could build on this by refining allocation principles and metrics, applying the framework to additional metals, technologies and regions, and integrating equity more systematically into energy and material modelling.

More broadly, the findings underline the importance of interdisciplinary research, connecting material flow analysis with questions of governance, and global justice. Understanding not only how much material is required and when, but also how it is distributed, remains central to designing transition pathways that are more feasible and equitable.

More broadly, the findings underline the importance of interdisciplinary research, connecting material flow analysis with questions of governance and global justice. Understanding not only how much material is required and when, but also how it is distributed, remains central to designing transition pathways that are more feasible and equitable. Overall, interactions between energy and material systems, supply and demand dynamics, and the links between supply chains and service provision, together with diverse policy pathways and societal debates across sectors and regions, create additional layers of complexity and emerging research challenges [31]. Addressing these challenges requires systems analysis and stronger integration of engineering and social science perspectives.

8.3 Limitations and uncertainty

8.3.1 System boundaries

Temporal system boundaries

Temporally, scenarios cover 2022–2050, with 2050 as the end year of the analysis. Given this horizon and the long lifespans of wind and solar technologies (see Table 4.2 in Chapter 4, *Methodology*), the full lifecycle of technologies introduced later in the period is not captured (see Figure 4.2 in Chapter 4, *Methodology*). This limits the extent to which the contributions of longer service lifespan and recycling strategies, as well as their interactions with other CE strategies and the resulting trade-offs, can be represented, as these are expected to persist beyond 2050.

Technology and material scope

Many metals are used across multiple applications, both within and beyond low-carbon technologies. REEs, for example, are used in wind turbine generators, electric vehicles, electronics, medical equipment, and increasingly in military applications [41,64,99]. Focusing on a single technology captures only part of total demand and therefore likely represents a conservative assessment. This applies to all appended articles. The findings should thus be interpreted in the context of broader material demand, even though the extent of cross-sectoral use is not quantified in this thesis.

In particular, for **Article I**, although only one decarbonization scenario (Renewable Electrification) is included in the presentation of the results in this thesis, the article assesses material dynamics in two additional scenarios: Decentralized Renewable and Dispatchable Electrification. Substantial differences are observed between the scenarios, especially between the Decentralized Renewable, which focuses on and Renewable Electrification cases, with the latter showing the highest demand for the REEs neodymium and dysprosium (for further details on scenario assumptions, refer to the Supplementary Material of **Article I**). While these findings are valid within the defined technology and material scope, it is important to recognize that REEs are also critical for other decarbonization technologies, particularly electric vehicles. Expanding the system boundary to include these applications could therefore significantly alter the observed demand trends. In the Decentralized Renewable scenario, for example, a high degree of sector integration between transport and electricity implies increased electrification of transport, and consequently higher demand for REEs beyond the power sector.

Similarly, in **Article IV**, the required production and reserves of HREEs indicate a clear constraint from an equity perspective, whereas LREEs do not. Nevertheless, when technology-specific demand already approaches or exceeds an allocation benchmark, total demand across all applications is likely to be substantially higher.

In **Articles II–IV**, the potential for substitution through novel technologies in wind and/or solar power is examined. In wind power, substitution includes both component-level changes, such as REE-free ferrite PM replacing REE-based magnets, and sub-technology-level changes, such as high-temperature superconducting (HTS) systems replacing PM-based designs. HTS generators can achieve higher efficiencies than REE-based PM wind turbines but rely on yttrium–barium–copper oxide materials [130]. Yttrium, baryte, and copper are all included in the EU's 2024 critical raw materials list, with copper also classified as strategic [72]. Ferrite-based PM offer a more abundant and cost-effective alternative with lower environmental impact, but with reduced magnetic strength, and increased size and weight [131].

In solar power, substitution includes perovskite-based technologies and silver-free c-Si panels. Perovskite solar cells, which have achieved rapid efficiency improvements in laboratory settings, typically contain lead iodide and methylammonium iodide [132]. The presence of lead raises environmental and health concerns [133]. At the same time, research into lead-free perovskite alternatives is advancing [134].

While such technologies eliminate the use of certain minor metals currently required, they introduce new materials and associated trade-offs. Therefore, while the system boundary of the analysis in terms of the metals included is focused on the metals used in existing technologies, broadening the system boundary to include potential substitutes would facilitate an understanding of the metal dynamics associated with the substitution.

8.3.2 Uncertainty

The analysis is subject to several sources of uncertainty.

First, the modelling of CE strategies relies on assumptions regarding technical potential and adoption rates. Although multiple market shares are explored, key parameters remain uncertain. One example is material intensity and its future reduction. The analysis in **Articles II–IV** is based on consistent assumptions regarding material intensities and their reduction rates. However, as illustrated by the wide ranges reported in the Supplementary Information of **Article II** (Tables S1.4–S1.19 and Figures S1.5 and S1.6), these parameters introduce substantial uncertainty, especially toward the end of the scenario period, where cumulative effects become substantial.

Another example is substitution. The model assumes certain rates of substitution, such as the uptake of REE-free magnet technologies, which are inherently uncertain. Even though the assumptions are based on literature, emerging technologies may penetrate the market more slowly or more rapidly than assumed, or alternative technological pathways may emerge. The results should therefore be interpreted as exploratory, illustrating possible developments under specific assumptions, rather than predicting the expected pace or scale of change.

Second, estimates of reserves and production as used in **Article IV** are inherently uncertain, as they depend on evolving economic conditions, technological developments, and geopolitical dynamics. These factors can alter both resource availability and production capacity over time.

Finally, the implementation of equity principles relies on proxy indicators, such as electricity consumption, GDP, and population projections. These proxies capture only part of the underlying concepts and are themselves uncertain due to their dependence on assumptions about future development pathways. Consequently, the allocation results should be interpreted as indicative of orders of magnitude rather than precise quantitative estimates.

Overall, this highlights the importance of transparency and regular updates of such assessments.

8.4 Directions for future work

8.4.1 Extending the temporal scope of the analysis

Since the analysis extends only to 2050, longer-term effects related to longer service lifespan and recycling are not fully captured (see Figure 4.2 in Chapter 4, *Methodology*). Exploring the effects of CE strategies over a longer time horizon represents an important direction for future research.

This would enable capturing more comprehensively the effects of slow and close CE strategies included in the work, as well as their interactions with the narrow strategies and the trade-offs introduced as a result. In particular, as shown in Section 6.3.3, a trade-off emerges between reducing gross demand and reducing primary demand when slow strategies are implemented alongside narrow and close strategies. This trade-off is time-horizon dependent. While the combined Slow–Narrow–Close strategies result in higher cumulative primary demand up to 2050, extending the analysis beyond this point would likely reduce this difference and may even reverse it. This outcome would depend on factors such as a plateau in renewable capacity expansion, the accumulation of effects from longer service lifespan and recycling, and the interplay of narrow and close strategies become more evident as material intensities are reduced resulting in less metal outflows for secondary supply.

8.4.2 Broadening the scope of metals and technologies

A key priority for future research is to extend the analysis beyond the materials currently studied to include additional materials required for the energy transition, alongside a broader range of technologies such as electric vehicles and energy storage systems. This would enable a more comprehensive assessment of material dynamics with regard to demand supply and equity considerations, competing demands for the same materials, and substitution possibilities across technologies. Substitution with new technologies, components or materials involves balancing the associated trade-offs for example in terms of technological performance, supply risk, and the social, environmental and economic impacts. Future research can investigate these potential trade-offs.

8.4.3 Examining alternative energy demand scenarios

Recent literature suggests that mitigation pathways rooted in broader socio-economic change, rather than primarily technology-driven transitions, may alleviate feasibility constraints associated with integrated assessment model scenarios used in IPCC assessments [8,135]. Accordingly, emerging post-growth and degrowth scenarios could be examined alongside mainstream energy system models.

8.4.4 Extending the scope of CE strategies

Future work could examine the individual and combined potential and possible trade-offs associated with other CE strategies than the ones explored in this work across technology lifecycle stages, including design and manufacturing, operation and maintenance, and EoL phases such as modularization, component reuse, repair, repurpose, and refurbishment.

8.4.5 Future directions for equitable allocation analysis

Extending the scope of equity principles

This study applies three equity principles, but several additional concepts have been proposed in the literature (Dooley et al., 2021), and their suitability for metal availability remains largely unexplored. Further refinement is also needed in the operationalisation of existing principles.

Defining metal budgets based on broader indicators

While production and reserve data capture important constraints on metal availability, additional factors such as environmental, social, and governance conditions increasingly determine whether deposits can be used.

The transition to a more metal-intensive energy system redistributes pressures across planetary boundaries [31,136–139]. Large-scale extraction can generate socio-environmental impacts that disproportionately affect marginalised communities [124,125]. Developing metal budgets that incorporate these broader sustainability and justice dimensions represents an important research direction.

An additional equity-oriented avenue for research involves defining metal budgets based on DLS. Such an approach would ground allocations in the material requirements necessary to ensure a minimum level of well-being. However, existing estimates of DLS-related material demand reflect current electricity mixes and technology assumptions, both of which are rapidly evolving. For application in forward-looking scenario analysis, DLS-based metal budgets would therefore need to be recalculated using decarbonisation-aligned technology portfolios.

Accounting for spatial heterogeneity in energy systems

Future research could also incorporate regional differences in renewable resource availability and electricity demand. Technology deployment varies significantly across regions due to differences in wind and solar resources, land availability, and social acceptance, while electricity demand is also location specific. Allocation frameworks could be further developed to explicitly account for such spatial heterogeneity.

CHAPTER 9

Conclusions

This thesis develops a dMFA model to examine the effects of CE strategies on embodied emissions, material demand and supply, and equitable material allocation in the deployment of renewable electricity technologies within decarbonization scenarios. Steel and concrete are included to assess CE effects on embodied emissions, and minor metals and REEs to evaluate effects on material demand, supply, and equity.

The results show that CE strategies can substantially reduce embodied emissions and material demand, although their effectiveness varies across materials and over time. For minor metals and REEs, material intensity reduction and substitution offer the greatest potential for near-term demand reduction, while recycling and longer service lifespan have more delayed effects. Differences across metals also emerge in the compatibility between required supply and equity-based allocation. Overall, the effectiveness of CE strategies is time-, metal-, technology-, and market share-dependent, indicating that no single strategy is sufficient and that tailored portfolios are required. A trade-off arises during the transition: strategies that reduce total material demand may increase reliance on primary supply. Nevertheless, their combined implementation can reduce cumulative primary demand by more than half and alleviate pressure on supply systems.

At the same time, the findings emphasize that even under ambitious CE implementation, emissions remain above net-zero targets, substantial primary demand and required supply persist, and equity-based constraints on metal availability remain binding. This highlights the need to complement CE strategies with broader efforts. These may include additional material demand reduction measures, energy demand reduction, and stronger integration of equity and fairness considerations in the energy transition.

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Appendix A: Language matters

Not only *matter matters*, language matters too. Behaviour is shaped by the stories we tell and the norms society reinforces, both of which are shaped by the language we choose [140]. Writing a thesis is, among other things, an opportunity to pause and reflect. In this section, I take the opportunity to reflect on the terminology used in industrial ecology, including the various terms I used during my PhD.

The words used to describe materials, technologies, and processes are not neutral. They shape how problems are framed, how solutions are imagined, and how responsibility is distributed. With this in mind, and while recognizing that terms embedded in research and policy are not easy to change, this section revisits a number of commonly used terms and considers their implications, while also, perhaps, daring to reimagine them.

"EoL, End of Life, END of LIFE..?!"

Perhaps the most persistent term worth questioning is *end-of-life* (EoL). The more I think about it, the more I see it as a linguistic legacy of linear thinking.

Calling something "end-of-life" suggests finality. A clear endpoint. But materials do not really have an end, do they? They are transported, transformed, or, in some cases, simply stored inefficiently in landfills. What is considered the "end" of one system is often the beginning of another. From this perspective, the end of a project is simply the start of a different project for someone else. When a wind park is decommissioned, for example, it becomes the beginning of a project for a decommissioning company. I often find myself thinking about those actors entering the system at that moment, stepping "in" exactly where the rest of the system says something has ended.

During discussions throughout my PhD with people working in CE, in academia, policy, and industry, several alternative terms came up, some more creative than others:

- EoU: End of Use. To some extent this term phases the same issue as the EoL. In addition, "use" also sounds to refer to consumer products, making it less suitable for renewable technologies.
- RfR: Ready for Reuse. When strictly looking at R-ladder, reuse is specific term. At the end of first operational phase, it is possible that components go towards several different directions: reuse, repurposing, refurbishing etc. making this term not suitable.
- OfO: Open for Opportunities. Appealing, but perhaps too optimistic for academic use ☺.
- EoOL: End of Operational Life. In case of wind turbines and solar panels, they are sometimes reused at new locations. Thus, they continue being operational elsewhere.

- DP: Decommissioning Phase or Dismantling Phase. This describes exactly that phase and does not limit options of what could still happen to the technologies afterwards. But then it calls for other terms for describing what can happen afterwards.
- EoFL/EoCL: End of First Life/ End of Current Life. That seems to be a more accurate term and points to completely different direction than EoL.

Some of these terms are catchy, some are precise, and some are neither. None are perfect. But they all do something important, they challenge the idea that there is ever truly an "end-of-life". Materials continue to exist and circulate, even if current systems fail to capture their value effectively.

Despite these conceptual limitations, "end-of-life" remains deeply embedded in both academic and policy discourse. For now, it is a term that I use, for consistency and shared understanding. Still, questioning it serves as a reminder that the language of CE has not fully escaped the linear paradigm it seeks to replace.

"Waste" management – or not?

On a similar note, the term *waste management* is remarkably persistent. It appears everywhere, in journal titles, policy frameworks, and institutional structures. But what if the problem is the word "waste" itself? Calling something waste implies that it has no value. It frames the challenge as managing disposal, rather than managing resources. From a CE perspective, this feels like a fundamental mismatch. What would happen if we consistently spoke about *resource management* instead? In a way, language here is lagging behind practice. If countries have been introducing landfill taxes since the 1980s and 1990s, implicitly recognising the value of materials, should our terminology not have evolved alongside?

"Circularity potential"

In **Article I**, I used the term *circularity potential* to describe the ratio of material outflows to inflows. While this usage exists in the literature [92], the term itself remains loosely defined and is applied in multiple ways [92,141]. As a result, it can obscure rather than clarify what is being measured. This became particularly evident in discussions with one of my supervisors during the development of **Article II**. We explored several alternative formulations and eventually moved away from the term altogether, settling on *demand–supply balance*, which more directly reflects the underlying calculation.

A broader issue arises in relation to the term "circularity" itself. In practice, and particularly outside expert communities, "circularity" is often used interchangeably with "recycling". But recycling is only one strategy, and, as shown throughout this thesis, often not the most effective one, especially in the early stages of the transition. I have found that replacing the phrase "recycling solutions" with "circular strategies" immediately opens up the conversation. It invites thinking beyond end-of-life interventions and towards slowing and narrowing material flows. Language, in this sense, does not just describe solutions, it shapes which solutions we are even able to imagine.

“Critical” and “bulk” materials

In **Article I**, I categorize materials as *bulk* (steel and concrete) and *critical* (neodymium and dysprosium). This terminology is common in the literature, yet it combines two fundamentally different types of classification. “Bulk” refers to a physical characteristic, large volumes, relatively stable across time and geography. “Critical”, on the other hand, is context-dependent, based on economic importance and supply risk. Materials are not inherently critical; they become critical under specific technological, geopolitical, and economic conditions. What is critical today may not be critical tomorrow. What is critical in one region may not be critical in another. This creates a subtle inconsistency: one term describes a physical property, the other a socio-economic condition.

In this thesis, I use an alternative framing: *structural* and *technology-specific* materials. From there, more precise categories such as REEs or minor metals can be introduced.

“Clean” energy technologies

In **Article I**, the term *clean energy technologies* is used to refer to renewable energy technologies and electric vehicles. While widely adopted, the term “clean” can be misleading. These technologies significantly reduce greenhouse gas emissions, yet they are associated with a range of other environmental and social impacts, including material extraction, land use, and supply chain effects, as discussed in the *Introduction chapter*.

For this reason, the term *low-carbon technologies* is considered more appropriate, as it more accurately reflects the specific dimension in which these technologies provide benefits, while leaving space to acknowledge trade-offs and unintended consequences.

“Virgin” materials

Throughout this thesis, the term *primary* or *raw* materials is used instead of “virgin” materials. This choice is deliberate. The term “virgin” has been critiqued for its gendered connotations, as it implicitly associates value and purity with a concept historically tied to women’s bodies and social norms [142]. While this association is not intended in industrial or scientific contexts, it is embedded in the language itself. Replacing “virgin” with “primary” maintains technical accuracy without carrying these unintended connotations. This may appear as a minor linguistic shift, but it reflects a broader principle: even technical terminology is not free from social meaning, and small changes in language can contribute to more inclusive and reflective scientific discourse.

Taken together, these examples illustrate that language is not just a passive tool for describing material systems, it actively shapes how those systems are understood and governed. Terms such as “critical”, “circular”, “clean”, or “end-of-life” carry implicit assumptions that influence both analysis and decision-making. Reflecting on language is therefore not merely a stylistic exercise, but part of the analytical work itself.


Vestas