THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Matter matters

Material flow analysis of renewable electricity generation technologies

GEORGIA SAVVIDOU

Department of Space, Earth and Environment

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2024

Matter matters
Material flow analysis of renewable electricity generation technologies

GEORGIA SAVVIDOU

Department of Space, Earth and Environment
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

Printed by Chalmers Digital Print

Gothenburg, Sweden 2024

Matter matters
Material flow analysis of renewable electricity generation technologies

GEORGIA SAVVIDOU
Division of Energy Technology
Department of Earth, Space and Environment
Chalmers University of Technology

Abstract

The mitigation of human-induced climate change requires the expansion of renewable electricity sources, such as wind and solar power. The material extraction and waste flows associated with these technologies will amplify environmental and social impacts on a planetary scale, endangering a sustainable energy transition. The circular economy has the potential to decrease both the magnitude of the decarbonization challenge and the associated demands for material resources. The role of the circular economy in *Closing* material loops through recycling in variable renewable electricity systems has gained attention. However, its potentials for *Slowing* down the flow of materials through prolonging the service lifespans of renewable technologies, *Narrowing* the material use per installed capacity, through material intensity reductions and substitution with novel technologies, and their combined impact on embodied emissions along the materials' supply chains, primary material demand and secondary supply availability remain underexplored.

Here, I use a prospective material flow analysis to assess these potentials with respect to the large-scale deployment of wind and solar photovoltaic power in the Swedish energy transition to 2050. This includes assessment of the potential for reducing embodied emissions related to the bulk materials, steel and concrete, essential for wind turbines and their foundations through circular economy strategies, longer service lifespan, and material intensity reduction. Furthermore, I investigate the potentials and trade-offs associated with reducing the primary demand and increasing the secondary supply availability for 11 minor metals through *Slowing*, *Narrowing* and *Closing* circular economy strategies.

The results show that longer service lifespan and material intensity reduction substantially reduce the embodied emissions of steel and concrete. Nonetheless, reductions in the production processes of these materials remain crucial for wind power to comply with Sweden's decarbonization target. *Narrowing* strategies exert the greatest impact on primary metal demand reduction over the scenario period. While achieving the climate mitigation target, combined implementation of *Slowing*, *Narrowing* and *Closing* strategies reduces by more than half the required cumulative primary demands for all metals, as compared to the absence of circular economy strategies. On an annual basis, towards the end of the scenario period, the *Slowing*, *Narrowing* and *Closing* strategies combined substantially reduce the primary demand for all metals, while eliminating the annual primary demand for two of them. However, primary demand remains necessary for the majority of the metals throughout the scenario period, highlighting the importance of developing effective and sustainable circular economy strategies, and also emphasizing the need for demand-side measures and responsible mining practices during an energy transition with a high reliance on variable renewable electricity. Although the findings indicate that by 2050, the secondary supply could meet more than half of the gross metal demand for the majority of the metals studied, the results also highlight the limited potential of recycling during the short-to-medium term phases of the energy transition with high shares of wind and solar photovoltaic technologies.

Full realization of the benefits of these circular economy strategies requires the exploration of opportunities at every stage of the supply chains of wind and solar photovoltaic technologies.

Keywords: *Variable renewable electricity, Material flow analysis, Circular economy, Bulk materials, Minor metals, Embodied emissions, Primary metal demand, Secondary supply, Trade-offs*

Περίληψη

Η μείωση της ανθρώπινης επιρροής στην κλιματική αλλαγή απαιτεί την επέκταση των ανανεώσιμων πηγών ηλεκτρικής ενέργειας, όπως η αιολική και η ηλιακή ενέργεια. Η εξόρυξη υλικών και οι ροές αποβλήτων που σχετίζονται με αυτές τις τεχνολογίες θα εντείνουν τις περιβαλλοντικές και κοινωνικές επιπτώσεις σε πλανητική κλίμακα, θέτοντας σε κίνδυνο τη βιώσιμη ενεργειακή μετάβαση. Η κυκλική οικονομία έχει τη δυνατότητα να μειώσει τόσο το μέγεθος της πρόκλησης της απανθρακοποίησης όσο και τις σχετικές απαιτήσεις για υλικούς πόρους. Ο ρόλος της κυκλικής οικονομίας στο *Κλείσιμο* των υλικών κύκλων μέσω της ανακύκλωσης σε συστήματα ανανεώσιμης ηλεκτρικής ενέργειας έχει προσελκύσει την προσοχή. Ωστόσο, οι δυνατότητές της για την *Επιβράδυνση* της ροής των υλικών μέσω της παράτασης της διάρκειας ζωής των ανανεώσιμων τεχνολογιών, τη μείωση της χρήσης υλικών ανά εγκατεστημένη ισχύ μέσω της μείωσης της υλικής έντασης και της *Υποκατάστασης* με νέες τεχνολογίες, και ο συνδυασμένος αντίκτυπός τους στις ενσωματωμένες εκπομπές κατά μήκος των αλυσίδων εφοδιασμού υλικών, τη ζήτηση για πρωτογενή υλικά και τη διαθεσιμότητα δευτερογενών προμηθειών παραμένουν ανεξερεύνητες.

Εδώ, χρησιμοποιώ μια προοπτική ανάλυση ροής υλικών για να αξιολογήσω αυτές τις δυνατότητες σε σχέση με την ευρεία ανάπτυξη της αιολικής και φωτοβολταϊκής ενέργειας στην ενεργειακή μετάβαση της Σουηδίας έως το 2050. Αυτό περιλαμβάνει την αξιολόγηση της δυνατότητας μείωσης των ενσωματωμένων εκπομπών που σχετίζονται με τα χύδην υλικά, όπως το ατσάλι και το τσιμέντο, τα οποία είναι απαραίτητα για τις ανεμογεννήτριες και τα θεμέλιά τους μέσω στρατηγικών κυκλικής οικονομίας, μεγαλύτερης διάρκειας ζωής και μείωσης της υλικής έντασης. Επιπλέον, διερευνώ τις δυνατότητες και τους συμβιβασμούς που σχετίζονται με τη μείωση της ζήτησης για πρωτογενή υλικά και την αύξηση της διαθεσιμότητας δευτερογενών προμηθειών για 11 μέταλλα μέσω στρατηγικών κυκλικής οικονομίας που *Επιβραδύνουν*, *Μειώνουν* και *Κλείνουν* τους κύκλους υλικών.

Τα αποτελέσματα δείχνουν ότι η μεγαλύτερη διάρκεια ζωής και η μείωση της υλικής έντασης μειώνουν σημαντικά τις ενσωματωμένες εκπομπές ατσαλιού και τσιμέντου. Παρ' όλα αυτά, οι μειώσεις στις διαδικασίες παραγωγής αυτών των υλικών παραμένουν κρίσιμες για τη συμμόρφωση της αιολικής ενέργειας με τον στόχο απανθρακοποίησης της Σουηδίας. Οι στρατηγικές *Μείωσης* ασκούν τη μεγαλύτερη επίδραση στη μείωση της ζήτησης για πρωτογενή μέταλλα κατά την περίοδο του σεναρίου. Ενώ επιτυγχάνεται ο στόχος μείωσης των κλιματικών επιπτώσεων, η συνδυασμένη εφαρμογή στρατηγικών που *Επιβραδύνουν*, *Μειώνουν* και *Κλείνουν* τους κύκλους υλικών μειώνει περισσότερο από το ήμισυ της απαιτούμενης συνολικής ζήτησης για πρωτογενή μέταλλα, σε σύγκριση με την απουσία στρατηγικών κυκλικής οικονομίας. Σε ετήσια βάση, προς το τέλος της περιόδου του σεναρίου, οι συνδυασμένες στρατηγικές που *Επιβραδύνουν*, *Μειώνουν* και *Κλείνουν* τους κύκλους υλικών μειώνουν σημαντικά τη ζήτηση για πρωτογενή μέταλλα, ενώ εξαλείφουν την ετήσια ζήτηση για δύο από αυτά. Ωστόσο, η ζήτηση για πρωτογενή υλικά παραμένει απαραίτητη για την πλειονότητα των μετάλλων καθ' όλη τη διάρκεια της περιόδου του σεναρίου, υπογραμμίζοντας τη σημασία της ανάπτυξης αποτελεσματικών και βιώσιμων στρατηγικών κυκλικής οικονομίας και επίσης τονίζοντας την ανάγκη για μέτρα ζήτησης και υπεύθυνες πρακτικές εξόρυξης κατά τη διάρκεια μιας ενεργειακής μετάβασης με υψηλή εξάρτηση από μεταβλητή ανανεώσιμη ηλεκτρική ενέργεια. Αν και τα ευρήματα δείχνουν ότι έως το 2050, η δευτερογενής προσφορά θα μπορούσε να καλύψει περισσότερο από το ήμισυ της ακαθάριστης ζήτησης μετάλλων για την πλειονότητα των μελετημένων μετάλλων, τα αποτελέσματα τονίζουν επίσης τον περιορισμένο δυναμικό της ανακύκλωσης κατά τις βραχυπρόθεσμες έως μεσοπρόθεσμες φάσεις της ενεργειακής μετάβασης με υψηλά ποσοστά τεχνολογιών αιολικής και φωτοβολταϊκής ενέργειας.

Η πλήρης αξιοποίηση των πλεονεκτημάτων αυτών των στρατηγικών κυκλικής οικονομίας απαιτεί την εξερεύνηση ευκαιριών σε κάθε στάδιο των αλυσίδων εφοδιασμού των τεχνολογιών αιολικής και φωτοβολταϊκής ενέργειας.

Resumen

La mitigación del cambio climático inducido por el ser humano requiere la expansión de fuentes de electricidad renovable, como la energía eólica y solar. La extracción de materiales y los flujos de desechos asociados con estas tecnologías amplificarán los impactos ambientales y sociales a escala planetaria, poniendo en peligro una transición energética sostenible. La economía circular tiene el potencial de disminuir tanto la magnitud del desafío de la descarbonización como las demandas asociadas de recursos materiales. El papel de la economía circular en el *Cierre* de los ciclos de materiales a través del reciclaje en sistemas de electricidad renovable variable ha captado la atención. Sin embargo, su potencial para *Desacelerar* el flujo de materiales mediante la prolongación de la vida útil de las tecnologías renovables, *Reducir* el uso de materiales por capacidad instalada a través de la reducción de la intensidad de materiales y la sustitución con nuevas tecnologías, y su impacto combinado en las emisiones incorporadas a lo largo de las cadenas de suministro de materiales, la demanda de materiales primarios y la disponibilidad de suministro secundario permanecen inexplorados.

Aquí, utilizo un análisis prospectivo de flujo de materiales para evaluar estos potenciales con respecto a la implementación a gran escala de energía eólica y solar fotovoltaica en la transición energética de Suecia hacia 2050. Esto incluye la evaluación del potencial para reducir las emisiones incorporadas relacionadas con los materiales a granel, como el acero y el hormigón, esenciales para las turbinas eólicas y sus cimientos, a través de estrategias de economía circular, una mayor vida útil y la reducción de la intensidad de materiales. Además, investigo los potenciales y las compensaciones asociadas con la reducción de la demanda primaria y el aumento de la disponibilidad de suministro secundario para 11 metales menores mediante estrategias de economía circular que *Desaceleran*, *Reducen* y *Cierran* los ciclos de materiales.

Los resultados muestran que una mayor vida útil y la reducción de la intensidad de materiales reducen sustancialmente las emisiones incorporadas del acero y el hormigón. No obstante, las reducciones en los procesos de producción de estos materiales siguen siendo cruciales para que la energía eólica cumpla con el objetivo de descarbonización de Suecia. Las estrategias de *Reducción* ejercen el mayor impacto en la reducción de la demanda de metales primarios durante el período del escenario. Mientras se logra el objetivo de mitigación climática, la implementación combinada de estrategias que *Desaceleran*, *Reducen* y *Cierran* los ciclos de materiales reduce en más de la mitad las demandas acumuladas de metales primarios requeridas, en comparación con la ausencia de estrategias de economía circular. Sobre una base anual, hacia el final del período del escenario, las estrategias combinadas que *Desaceleran*, *Reducen* y *Cierran* los ciclos de materiales reducen sustancialmente la demanda primaria de todos los metales, eliminando la demanda primaria anual de dos de ellos. Sin embargo, la demanda primaria sigue siendo necesaria para la mayoría de los metales a lo largo del período del escenario, lo que subraya la importancia de desarrollar estrategias de economía circular efectivas y sostenibles, y también enfatiza la necesidad de medidas del lado de la demanda y prácticas mineras responsables durante una transición energética con una alta dependencia de la electricidad renovable variable. Aunque los hallazgos indican que para 2050, el suministro secundario podría satisfacer más de la mitad de la demanda bruta de metales para la mayoría de los metales estudiados, los resultados también destacan el limitado potencial del reciclaje durante las fases a corto y medio plazo de la transición energética con altas participaciones de tecnologías eólicas y solares fotovoltaicas.

La plena realización de los beneficios de estas estrategias de economía circular requiere la exploración de oportunidades en cada etapa de las cadenas de suministro de tecnologías eólicas y solares fotovoltaicas.

List of publications

This thesis is based on the following papers:

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

II. Savvidou, G., Johnsson, F., Ljunggren, M., Liu, Q., Tasseven, U., Zachariadis, T., 2024. Technological Advancements Can Halve Minor Metal Demand in Large-Scale Wind and Solar PV Deployment. Submitted for journal publication.

Georgia Savvidou is the principal author of **Papers I** and **II** and was responsible for conceptualization, methodology development, formal analysis, visualization, and writing of original drafts. Professor Filip Johnsson contributed with discussions and reviewing of both papers. Associate Professor Maria Ljunggren contributed with discussions and editing of **Paper II**. Qiyu Liu contributed with software support, methodology discussions, and reviewing of **Paper II**. Ulku Tasseven has contributed to **Paper II** with review and discussions. Professor Zachariades has contributed with reviewing **Paper II**.

Additional publications not included in the thesis:

- Savvidou, G., Johnsson, F., Liu, Q., 2023. Bridging Climate and Circular Economy Related Policy Targets: Insights from Material Requirements in the Renewable Electricity System. *Conference paper (peer-reviewed) presented at the 7th International Conference on Renewable Energy Sources and Energy Efficiency (RESEE2023).* Nicosia, Cyprus.

- Tasseven, U., Zachariadis, T., Savvidou, G., Liu, Q., Johnson, F., 2024. From Fossil Fuel- to Material-intensive: A Material Flow Analysis of Cyprus' Photovoltaic Transition to Net-Zero Emissions by 2050. To be submitted for journal publication.

- 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

Acknowledgments

Starting my PhD during the COVID-19 pandemic and not moving to Gothenburg until about a year into the program was not what I would call a smooth beginning to a PhD journey. Moving from an interdisciplinary team at the Stockholm Environment Institute to a team with a strong engineering identity, while not being an engineer myself, has made me reflect a lot on my journey in trying to find my identity as a researcher and a sense of belonging. Over the past three years, I have learned a great deal, and I feel that I've grown both professionally and personally. As I write this text and reflect on the past three years of my PhD journey, it is time to express my gratitude to those who have helped me along the way.

Filip, I am grateful for the time and resources you have invested in engaging with my research, and for the flexibility and trust you have provided along the way. Maria, you joined my PhD journey relatively recently. Thank you for all the support so far. I'm looking forward to seeing what we can develop over the remaining time of my doctoral journey.

A PhD journey comes with ups and downs. Anna, thank you for the genuine excitement and celebration during the ups, and for being an empathetic, active listener, and truly supportive during the downs.

Aaron, thank you for your dedication to what I guess felt like endless hours of MFA discussions and whiteboard scribblings.

Ulku, collaborating with a fellow Cypriot, especially from across the divide, has been a dream for me. Having that collaboration with you in particular has been a challenging and learning journey that I am grateful for. In you, I found a friend.

To my colleagues at EnTek, thank you for the fun discussions over lunch and the friendly encounters in the corridors. To the informal sustainability group, thank you for creating a safe space for sharing and for the trust that we are ready to support each other whenever needed. Thank you to my colleagues from ESA for welcoming me into your team.

Simon, thank you for putting up with my growing desire for new plant officemates 🪴. I can't promise that it won't continue.

To my various mentors or friends from Chalmers and the Stockholm Environment Institute and other places—Elias, Helene, Björn, Biljana, Timo—thank you for being there providing guidance during difficult times.

Carl-Joar, Angelica, Leon, Maria, Elena, Rebecka, Vi, Kelsey, Achintya, Malin, Rana —aka the Dr. Genie team—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 a continuous one. I'm in awe of your dedication to our cause, and your energy inspires me! Lauri, thank you for helping us see in each other and build trust. For teaching us about leading with empathy, about the power of influence, inclusive leadership, and more.

To all the previous steering committee members of the network Women and Inclusivity in Sustainable Energy Research (WISER), I'm proud of the work we did together over the past three years and all the events we organized. Joining you, a group of social scientists, has been a journey out of my comfort zone, naturally connected with many learnings I feel grateful for. To the new steering committee, excited to see your WISER journey!

Gaby, your weekly yoga class is what I call my weekly present to myself! Your use of storytelling in your sessions is a gift to us—a getaway from PhD stress and an opportunity to feel grounded. Thank you, Chalmers, for providing the wellness hour. Employers around the world, get inspired!

Julien, thank you for dragging me out of my bubble when I was going through one of my PhD lows.

Angele, I am grateful to be exploring this path of self-discovery with you and can't wait to see where it takes me.

Mom and Dad, you paved the way for this in ways I'll probably never fully comprehend, and I am forever grateful for that. Mom, you were not given the opportunity for the education you deserved, so you wanted to make sure that all your children would finish university. With one postgraduate diploma, one PhD, and one PhD in the making, I'd say you overachieved your goal! Dad, your love for nature and growing your own food is something that I did not appreciate as a kid, but it is something I hope to continue being inspired by and learning from as an adult. Christiana, your spontaneous, joyous spirit during our calls reassure me that even though I'm far away for about 10 years already, some things back home continue just as crazy as they always have. Olympia and Panayiota, your drawings are in my office inspiring me every day. Seeing you growing up and becoming your own persons is a life lesson. Savva, having a brother who's completed a PhD means I know who to call in the family when I need support ;) We may have different PhD experiences, but your genuine care means a lot.

Eddie, I'm not sure how to describe my gratitude for you in words. Thank you for believing in me even when I don't, for the late food deliveries at Chalmers, for the patience, the understanding, for the immense support.

Despite the challenges I've encountered, I recognize that my journey as 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 through a project at the Stockholm Environment Institute that started well before I joined Chalmers. 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'm deeply privileged. Through my research here at Chalmers, I developed an understanding of the deep injustices embedded in the supply chains of highly valued materials needed for, among other things, the energy transition. If I could wish for one insight that my future research could contribute to, it is how living simpler can reduce social and ecological injustices (in the Future Work chapter, I give some half-formed thoughts on this). Continuing on the topic of privilege but on a different level, I'm aware of how academia can be a precarious place for many. Being in academia in one of the few countries that treats a PhD as a full employment, with all the benefits this entails, is a privilege few of us have. Enjoying flexible working hours, and the flexibility and trust from my supervisors, are yet more privileges. The security of having employment after the end of my PhD is yet another, significant one.

Finally, I want to end by saying that *it takes a village*. If I were to acknowledge everyone who has supported me, 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.

Still in search of my research identity and my inter-/un (?)-disciplinary scientific family. Curious about what the journey will bring.

Georgia Savvidou, Gothenburg, September 2024

“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.”

“The choice, after all, is ours to make”

Rachel Carson

“We must learn how to restore to nature the wealth that we borrow from it”

Barry Commoner

“One individual cannot possibly make a difference, alone. It is individual efforts, collectively, that makes a noticeable difference - all the difference in the world!”

Jane Goodall

Table of contents

1. Introduction 1
1.1 Related work 2
1.2 Aims and scope 5
1.3 Content of the appended papers and the introductory essay 5
1.4 Outline of the thesis 6
2. Methodology 7
2.1 Material flow systems terms and modelling procedures 7
2.2 MFA modeling framework 9
2.3 Scenario setting 10
3. Selected results and discussion 17
3.1 Impacts of CE strategies on embodied emissions 17
3.2 Impacts of CE strategies on primary demand 19
3.3 Impacts of circular economy strategies on secondary supply 23
3.4 Trade-offs between circular economy strategies 26
3.5 Discussion on terminology, technology development assumptions, system boundaries, and methodology 30
4. Conclusions 35
5. Future work 37
Appendix A: Recycling analysis 41
Appendix B: Secondary supply availability 45
References 46
Reflections on inequities in academia 54
Reflections on academic flying 56

1. Introduction

Historically, energy transitions have been closely linked to the demands for materials, largely shaping and being shaped by the material foundations of societies [1]. Arising from the development of the energy infrastructure, and other provisioning systems, such as food production and transport systems, the global society's material foundation has expanded from 13 known elements before 1750 to more than 100 confirmed chemical elements currently. However, up until about 25 years ago, knowledge was limited regarding material usage rates, material accumulation, recycling efficiency, the dissipation of materials to the environment, and other relevant factors [2]. Since then, there has been an increased awareness of the importance of such knowledge and various types of analysis, including Material Flow Analysis (MFA) have been developed to provide these critical pieces of information [2].

Low-carbon energy technologies, such as wind and solar photovoltaics (PV), are crucial for mitigating human-induced climate change [3]. Despite the potential role of degrowth [4] and low-energy-demand scenarios [5] they will need to be greatly expanded to handle both the decarbonization of the existing electricity system and electrification of the industry and transport sectors [1]. As fossil fuels are gradually replaced by renewable energy and other low-carbon technologies, the future low-carbon energy system is expected to require less overall mining compared with the existing fossil fuel-based system [6]. Furthermore, unlike fossil fuels that are burned and lost permanently, the materials accumulated in low-carbon technologies remain in the urban mine and can, in theory, be re-circulated [7], [8].

Still, low-carbon technologies, including wind turbines and solar panels, along with their associated infrastructures, are material-intensive [9], and are particularly more mineral-intensive [10] than fossil fuels. Consequently, the global demands for the materials required to produce variable renewable electricity (VRE) are anticipated to rise significantly [11], [12], [13], [14]. As the adoption of wind and solar PV 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 [15], [16], their sourcing from and sinking to the Earth through mining and end-of-use waste, respectively, will amplify environmental and social pressures globally. Environmental impacts include increased land, air, and water pollution [17], [18], [19], [20], biodiversity loss [21] and greenhouse gas (GHG) emissions related to their supply chains [12], [22]. The latter particularly motivates the quantitative assessment of bulk materials. The concrete production and steelmaking industries, which supply two of the main bulk materials for wind turbines and their foundations, together account for about one-eighth of global greenhouse gas (GHG) emissions [23], and are considered hard-to-abate sectors [24], [25]. If measures to reduce GHG emissions are not applied to the processing industries, the GHG emissions associated with bulk materials could make up 10% of the remaining carbon budget for a 50% chance of limiting global warming to 1.5°C [12].

In terms of social impacts, the energy transition, as currently planned, carries the risk that the increased burden of mineral extraction will be disproportionately placed on low-income or Indigenous communities [26], [27], and there will be greater inequities within and between the countries in the Global North and Global South [28]. Overall, a large body of literature reveals that supply-side solutions to support the energy transition will exacerbate and intensify social and ecological injustices [27], [29], [30] and further impede global sustainability goals [31], [32]. The substantial footprint associated with material extraction, and waste generation on a planetary scale, driven by the supply-side decarbonization strategies that currently predominate, raises critical research questions that require new analytical tools to represent both the energy and material dimensions of decarbonization pathways [28].

In this context, the Circular Economy (CE) is presented as a key solution to mitigate effectively the climate and material risks associated with the rapid expansion of low-carbon technologies [28]. The concept of CE is not a recent development. It was theoretically established in the field of industrial ecology in the early 1990s [33], although its core principles are rooted in earlier works, including Rachel Carson's "Silent Spring", which was first published in 1962 [34], and Barry Commoner's "Four Laws of Ecology" [35]. The Ellen MacArthur Foundation has been instrumental in advancing the shift towards a CE within the business community. Despite its potential trade-offs [36], [37], CE is gaining recognition as a promising approach to addressing sustainability challenges linked to the energy transition [38]. In certain sectors, it is considered the 'third pillar' of deep decarbonization, following energy efficiency and low-carbon energy supply [39], [40].

In 2016, Bocken et al. [41] introduced the "Slow – Narrow – Close" framework of resource loops for strategies to move from a linear to a CE. *Slowing*, 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). *Narrowing* is about reducing resource use per unit of product. *Closing* refers to the closing of the resource loop between the end-of-use and production stages of a product's lifecycle, thereby creating a circular flow of resources. This is achieved through recycling.

In 2021, Velenturf [42] expanded this framework by integrating sustainable CE strategies throughout the technology lifecycle. In particular, they focused on offshore wind energy and categorized CE strategies along the technology lifecycle, differentiating between strategies that can be implemented during the technology design and manufacturing, operation and maintenance, and end-of-use management phases.

Another useful categorization for CE strategies in relation to VRE sources is their potential impacts over time, differentiating between strategies that have short-term and long-term impacts on resource use. For wind and solar PV power, for example, the potential impacts of strategies such as recycling, reuse, and lifespan extension to reduce primary demand are concentrated in the long-term of the energy transition period. This is due to the more than two decades lifespans of VRE technologies, as well as their associated rapidly growing demands, and in the case of recycling of minor metals, owning to the currently non-existent end-of-life (EoL) recycling capacities for the majority of the minor metals used in VRE technologies (see Supplementary Table S1 of **Paper II**).

1.1 Related work

The dynamics of the material requirements of VRE for low-carbon transition pathways have been explored extensively at the global level [10], [11], [12], [43], [44], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53], [54], and to a lesser extent at the European level [19], [55], [56], [57], [58] and national level [13], [59], [60], [61], [62]. These studies have addressed various issues related to the material demands for wind and/or solar PV technologies in low-carbon transition scenarios for different geographic and temporal scales, technological details, and material coverages.

Within this broad literature space, a subset includes the impacts of CE strategies in the material requirements of VRE sources in low-carbon transition pathways (see Table 1). Prospective studies on material dynamics including CE strategies have focused primarily on the Closing recourse loops strategy (recycling), which as mentioned earlier has a limited impact in the short-term. The impacts of CE strategies on technology design improvements for wind and solar PV technologies, such as material intensity (MI) reductions through material efficiency improvements and substitution[A] [Narrowing strategies], and the prolongation of the service lifespans of these technologies (longer service lifespan) [Slowing strategy], have been studied to a far lesser extent than recycling (see Table 1).

Substitution, in particular, has been relatively underexplored, and primarily focused on substitution with sub-technologies that are already commercial. Indeed, as recognized by Lee et al. [13], considering the recent industrial announcements regarding substitutions with novel applications for both wind (high-temperature superconducting (HTS) technologies and ferrite-based permanent magnets) and solar PV (perovskite solar cells and silver-free crystalline silicon panels), this is an area of growing interest. These technologies are progressing towards commercialization, as indicated in several industry announcements [63], [64], [65], [66]. As these novel technologies continue to develop, it becomes increasingly important to investigate their impacts on demands for materials, despite their potential associated trade-offs.

Longer service lifespans through improved technological designs are important to study particularly for onshore wind power, which has seen substantial growth since the early 2000s in many countries. Although wind power plants with guaranteed 30-year lifespans are already being commissioned (S. Fogelström, Swedish Wind Centre, personal communication, May 3, 2023), most studies still use a lower than or equal to 25-year lifespan throughout scenario periods [10], [12], [13], [15], [45], [67], [68], [69], [70], [71], [72], [73]. Given that a substantial portion of existing wind power capacity is expected to reach its EoL in the coming years, assessing the impacts of longer service lifespans becomes important.

With the exception of Li and Adachi [74], who have focused on only one solar PV sub-technology (c-Si) and one metal (Ag), there has been no study (see Table 1) examining the combined potential of all four strategies, namely Longer service lifespan, MI reduction, Substitution, and Recycling, to reduce the material demands. Considering that previous studies have demonstrated the substantial potentials of these strategies to lower the primary material demand, exploring these strategies in combination could offer valuable insights into addressing the material supply challenges. Furthermore, covering the entire spectrum of Slowing, Narrowing, and Closing strategies allows the investigation of potential synergies and trade-offs between the three distinct types of CE strategies, as well as their impacts on the gross demand, primary demand and secondary supply.

Finally, wind and solar PV technologies are considered key to transitioning to an emissions-free electricity system. However, such a system necessitates the consideration of the emissions along the supply chains of the materials, especially the bulk materials, along with the technologies' operational emissions. Still, the embodied emissions in the demand for VRE technologies are frequently overlooked in the literature [12] (also see Table 1).

Overall, the primary aim of this thesis is to contribute to understanding of the impacts of CE strategies spanning the spectrum of Slowing, Narrowing and Closing strategies, on embodied emissions, the primary demand, and the secondary supply of materials in relation to VRE generation (wind and solar PV power) during the energy transition to a decarbonized society with high shares of VRE by synthesizing, and expanding on, the work of the appended papers. The focus is on a national energy transition using Sweden as a case study.

[A]At the material, component or sub-technology layer. A sub-technology refers to a specific subset within a broader technology. For details on the material, component and sub-technology layers of wind and solar PV technologies see Table 2.

Table 1: Dynamic material flow studies in the literature that have evaluated the prospective demands for minor metals and/or bulk materials from low-carbon technologies, including circular economy strategies. Several of the studies include other technologies in addition to wind and solar PV. Adapted from Table 1 of **Paper II**.

Wind and/or solar PV inclusion	Region	Scenario final year	Circular economy strategies included	Embodied emissions studied	Materials Included	Study
Wind	Global	2050	Recycling, MI reduction, Substitution, Reuse	No	Nd, Dy, Pr, Tb	[67]
	Global	2040	Recycling	No	Nd, Pr	[45]
	Denmark	2050	MI reduction, Longer service lifespan	No	Nd, Dy, steel, cast iron, nonferrous metals, polymer materials, fiberglass, concrete	[60]
	US	2050	MI reduction	No	Nd	[68]
	Global	2100	Recycling	No	Dy, Nd	[69]
Solar PV	Global	2050	MI reduction, Substitution	No	Al, Si, Cu, As, Sn, Bi, Ga, Ag, Pb, In, Se, Zn, Ni, Cd	[75]
	Global	2050	MI reduction	No	Ge, Cd, Te, In, Ga, Se	[76]
	Global	2050	Recycling, MI reduction, Longer service lifespan, Substitution	No	Ag	[74]
	Global	2070	Recycling, MI reduction	No	Si, Ag, In, Ga, Se, Te, Cd	[16]
Wind and solar PV	Spain	2050	Recycling, MI reduction, Longer service lifespan	Yes	Al, Cu, Co, Li, Mn, Ni, Au, Ag, Pt, Pd, Dy, Nd	[62]
	US	2050	Recycling, MI reduction, Substitution	No	Cr, Zn, Ga, Se, Mo, Ag, Cd, In, Sn, Te, Pr, Nd, Tb, Dy, Pb	[13]
	Global	2050	Recycling	Yes	Al, cement, Cu, fiberglass, glass, Mn, Mi, Si, steel, Cd, Dy, Ga, In, Nd, Se, Ag, Te	[15]
	The Netherlands	2050	MI reduction, Longer service lifespan	No	Steel, Al, Cu, Ag, Cd, Ga, In, Ge, Si, Nd, Dy, Tb, Li, Co	[61]
	China	2050	Recycling, MI reduction, Longer service lifespan	No	Ag, Te, In, Ge, Se, Ga, Cd, Nd, Dy, Pr, Tb, Pb, Cu, Ni, Al, Fe, Cr, Zn	[77]
	Global	2060	Recycling, MI reduction	No	In, Ga, Se, Te, Cd, Ag, Dy, Nd, Li, Co, Ni, Pt, Fe, Al, Cu	[10]
	Global	2060	Recycling, MI reduction, Substitution	No	Ag, Nd, Dy, Co, Pt, In, Te, Cu, Ga, Li, Ni, Se	[70]
	Global	2050	Recycling	No	Nd, Dy, In, Ga, Se, Te, Cd, Ge, Ag, Mo, Cu, Cr, Ni, V, Pb, Sn, Al, Fe, Si, Ti, Zn, Ar, Mg, Mn, K, P	[78]
	Global	2050	Recycling	No	Nd, Dy, Pr, La, Ce, Gd, In, Ga, Se, Te, Cd, Ge, Ag, Mo, Cu, Cr, Ni, V, Sn, Al, Fe, Ti, Zn, Mg, Mn, Li, Pd, Pt, Ta	[71]
	Global	2100	Recycling, MI reduction, Longer service lifespan	No	Nd, Dy, In, Ga, Se, Te, Cd, Ag, Mo, Mn, Mg, Cu, Cr, Al, Ni, Fe, Li, Co, Va, Zr, Pt, Pd, La, Y, Hf, Ti, B, W, Nb	[52]
	Global	2050	Recycling	No	In, Te, Se, Cu, Dy, Nd, Y, Pt	[72]
	Global	2050	Recycling, Longer service lifespan	No	Ag, Nd, Pr, Dy, Tb, Y, La, Ce, Eu, Co, Pt, Ru, In, Te	[48]
	USA	2040	Recycling, MI reduction	No	Ag, Cd, Te, In, Ga, Se, Ge, Nd, Pr, Dy, Tb	[73]
	Global	2050	MI reduction	Yes	Concrete. Steel, Al, Cu, Fe	[12]

1.2 Aims and scope

The specific aims of this thesis are to:

(i) Investigate the roles that CE strategies (Longer service lifespan and MI reduction) can play in reducing embodied emissions related to *bulk materials* used in wind turbines and their foundations in a scenario of large-scale wind deployment.

(ii) Estimate and compare the impacts of CE strategies (Longer service lifespan, MI reduction, Substitution, and Recycling) on the primary *minor metal* demand in wind and solar PV technologies during large-scale wind and solar PV deployment.

(iii) Estimate the combined impact of CE strategies (Longer service lifespan, MI reduction, Substitution, and Recycling) on the secondary supply availability of *minor metals* in wind and solar photovoltaic technologies during large-scale wind and solar PV deployment.

(iv) Identify any potential trade-offs between reducing the gross and primary *minor metal* demands and increasing the secondary supply availability introduced by the studied CE strategies.

(v) Discuss how the terminology used, technology development assumptions made, system boundaries established, and methodological choices influence the modeling results, and/or the conclusions associated with the work of this thesis.

1.3 Content of the appended papers and the introductory essay

The aims of the thesis were investigated in two papers, as well as the synthesis and expansion of the work in the introductory essay of the thesis.

In particular, Paper I develops a modeling methodology to analyze the material flows in wind energy systems, and investigates the following research questions:

- What are the quantities of materials that will be required for wind power in different electricity decarbonization scenarios?
- What is the potential availability of secondary materials from the wind turbines and their foundations during the energy transition period?
- How much embodied emissions are associated with the steel and concrete requirements for wind turbines and their foundations during the transition period?

Overall, **Paper I** analyzes the stocks and flows in the wind power system towards 2050 in three energy transition pathways with varying wind installed capacities. This analysis includes the demands for two bulk materials used in all wind sub-technologies and their foundations, and two minor metals used in wind sub-technologies containing permanent magnets (See Table 2). It is conducted through a dynamic MFA using Sweden as a case study. The results for the bulk material inflows are used as the basis for estimating the embodied carbon emissions up to 2050 under different assumptions related to emissions control and rates of industrial development. While not explicitly presented in **Paper I**, the methodology includes two CE strategies: Longer service lifespan; and MI reduction, for which sensitivity analyses are conducted. Overall, work carried out in **Paper I**, directly contributes to Specific Aims *(i)*, *(iv)*, and *(v)* of the thesis.

Paper II further develops the methodology of **Paper I** to investigate the impacts of individual CE strategies related to technology design improvements, including the MI reduction, Longer service lifespan, and Substitution with novel technologies scenarios, as well as the impact of a combination of these strategies. It expands the methodology to include solar PV, in addition to wind power in its system boundary. It focuses on 11 minor metals used in wind power sub-technologies that contain permanent magnets (see Table 2). Sweden is used as a case study in this paper also. **Paper II** addresses the following overarching research question:

- What are the impacts of CE strategies related to technology design improvements (Longer service lifespan, MI reduction and Substitution with novel technologies) on the demand for minor metals, and what are their potentials for closing the metal loops during rapid expansion of the wind and solar PV technologies for the energy transition period up to 2050, so as to meet the climate mitigation target?

Overall, the work conducted in **Paper II** contributes to Specific Aims *(ii)*, *(iii)*, *(iv)*, and *(v)* of the thesis.

The introductory essay of this thesis expands the scope of CE strategies included by adding a Closing strategy, namely Recycling. This enables the investigation of the potential of recycling compared to other CE strategies, the investigation of a scenario combining strategies from the Slow-Narrow-Close framework, as well as the presentation of the results in terms of the primary demand and the secondary supply, in addition to the gross demand alone (as presented in the appended papers).

Table 2: Technology, sub-technology, component, and material layers of wind and solar PV technologies included in the thesis. The inclusion of technologies, sub-technologies, components and materials in **Papers I & II** is denoted. Source: Adapted from **Paper II**.

Technology layer	Sub-technology layer	Component layer	Material layer
Wind (onshore & offshore) **Papers I & II**	Direct-drive permanent magnet synchronous generators (DD-PMSG) **Papers I & II** Gearbox permanent magnet synchronous generators (GB-PMSG) **Papers I & II** Remaining sub-technologies **Paper I**	Rare earth element (REE) permanent magnets (PM) **Papers I & II**	Bulk materials: Concrete, Steel **Paper I** Minor metals: Neodymium (Nd), Praseodymium (Pr) **Papers I & II** Dysprosium (Dy), Terbium (Tb) **Paper II**
Solar PV (grid-connected [distributed & centralized]) **Paper II**	Crystalline silicon (c-Si) Amorphous silicon (a-Si) Cadmium telluride (CdTe) Copper indium gallium diselenide (CIGS)	-	Minor metals: c-Si: Silver (Ag) a-Si: Germanium (Ge) CdTe: Cadmium (Cd), Tellurium (Te) CIGS: Indium (In), Gallium (Ga), Selenium (Se)

1.4 Outline of the thesis

The thesis consists of the introductory essay and two appended papers. The introductory essay comprises five chapters that synthesize key outcomes of the appended papers and place the research in context. Following this introductory chapter, Chapter 2 introduces the concepts that are central to the methodology applied in the work and presents a short overview of the modeling framework and the scenarios developed within this work. The main findings of the work are presented and discussed in Chapter 3. Conclusions are drawn in Chapter 4 and future work is presented in Chapter 5.

2. Methodology

This chapter provides an overview of the methodology developed in the work, which relies on Material Flow Analysis linked with scenario development based on Circular Economy strategies, as applied in **Papers I** and **II**, as well as this introductory essay. **Paper I** develops an MFA model for wind power. **Paper II** improves the representation of wind power from **Paper I** in terms of the inclusion of metals, and their intensities, as well as the sub-technology market shares and technology lifespans. **Paper II** also expands the methodological framework to include solar PV power.

Section 2.1 introduces the main terms and modelling procedures needed to analyze, describe, and model material flow systems, which are essential for understanding the modeling framework applied to generate results for this thesis. The modelling framework is then presented in Section 2.2, followed by a presentation of the CE scenarios studied in the introductory essay of this thesis in Section 2.3.

2.1 Material flow systems terms and modelling procedures

In similarity to the biological processes comprising metabolism, which involve the flow of material and energy through our human bodies, 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[2] that is generated during these processes. These flows of resources into and from a particular industrial system, known in the industrial ecology field as *industrial metabolism*, can be mapped and quantified by Material Flow Analysis (MFA) which is one of the central methodologies of industrial ecology.

Terms that are essential to understanding the MFA methodology are: *processes, stocks, flows,* and *systems [79]*. Furthermore, terms that have been developed to describe the type of MFA that can be conducted based on its system boundaries are: *static* vs *dynamic, retrospective* vs *prospective*. In addition, there are those used for the research question/aim of conducting MFA: *inflow-driven* vs *stock-driven*. The following paragraphs define these terms, followed by an overall definition of MFA.

A *process* is defined as the transportation, transformation or storage of materials. 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 rare earth elements (REEs) in strategic reserves (storage). In MFA studies, the processes can cover a part of, or the entire, lifecycle of a material. For example, an MFA for a metal can cover one or all of the following processes: primary mining, raw material production, product manufacturing, use phase, and EoL management. Examples of the latter are landfilling and environmental or other repositories, representing the final sink of the assessed metals. Even though, in principle, MFA methods can be applied to any material, to date, it is metals that have been primarily studied due to the availability of relevant data [2]. In most of the models, the use phase is the only process that stores materials, while the other phases transport or transform them. An exception to this assumption is the storage of valuable metals for reasons of financial speculation or as strategic reserves).

[2]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 for the same or other processes. However, in our current industrial systems, materials and/or products often end up in landfills following their useful life, thereby constituting waste.

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 accumulation of materials), decrease in size (resulting in 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 [80].

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

Finally, a *system* consists of a set of 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. System boundaries are often defined by administrative regions, such as nations, states, or cities, since data are systematically collected at these levels. One benefit of this approach is that political and administrative stakeholders are located within the same regional boundary, making it easier to implement measures based on the results of the MFA in these administratively defined areas [79]. The temporal boundary depends on the type of system being examined and the specific problem at hand. It is the period of time over which the system is analyzed. It can theoretically range from 1 second for a combustion process to 1,000 years for a process such as landfilling. For anthropogenic systems., such as an organization, a city, or a country, periods of 1 year are typically chosen due to data availability, since the reporting of different types of inventories is usually conducted on an annual basis.

Material Flow Analysis entails a systematic assessment of the *flows* and *stocks* of materials within a *system* defined in space and time [79]. It is based on the law of conservation of matter [79], such that a material balance of the inflows, stocks, and outflows of resources in a *process* is established. An MFA provides 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 behavior of a system over a period of time [80]. 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, a dynamic MFA, developed by Baccini and Bader [81] 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 dynamic MFA can provide insights into factors that affect resource usage and can provide early warnings of associated environmental issues

[79]. 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 either *retrospective*, analyzing 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 analysis 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.

Making use of the terms defined in this Section, Section 2.2 presents the modeling framework developed in this work.

2.2 MFA modeling framework

The demand for new wind and solar PV in Sweden is driven by the increase in electricity demand linked to the electrification of the industry and transport sectors, as well as the need to replace the existing wind and solar PV technologies as they reach their EoL. To address these issues, *retrospective* and *prospective* analyses were performed in **Papers I** and **II** to estimate the demand for new capacity and the capacity for decommissioning over time. In this introductory essay, the temporal system boundaries comprise of the historical period of 1996–2021 and the scenario period of 2022–2050.

Central to the models in both papers are a *dynamic stock-driven* and *inflow-driven* MFA model (Figure 1, core model). Given the historical and future (based on scenarios) installed capacity of wind and solar PV, which is 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 MI coefficients. These are then fed into a dynamic inflow-driven MFA, resulting in *outflows* and *in-use stock* for the materials.

Papers I and II further expand on this core framework to address the research questions posed (as presented in the *Introduction*). The model applied in **Paper I** breaks down the capacity and material demand needed into a demand for expansion of wind and demand for replacement of existing capacity that is reaching its EoL. The model further calculates the embodied emissions related to the steel and concrete demand for wind power (Figure 1). The modelling framework of **Paper II** estimates the impacts of CE strategies related to technology design development, i.e., Longer service lifespan, MI reduction, and Substitution with novel technologies, with regards to the minor metal demand and demand-supply balance. Detailed graphical representations of the model structures, including the input data, main calculations, and output data, as well as descriptions and main assumptions on the model parameters and variables can be found in **Papers I** and **II.** Here, a graphical representation of the model components from **Papers I** and **II** relevant to the presentation of the results included in this introductory essay, along with the new components introduced, is presented in Figure 1.

In terms of CE strategies, Figure 2 organizes the four CE strategies included in the introductory essay of the thesis for wind and solar PV power based on their effects on resource flows, their impacts in time, and their stages throughout the technology infrastructure lifecycle, as described by Velenturf [42]. Their inclusion in the papers appended to the thesis is indicated by purple shading. In particular, **Paper I** includes the slowing and narrowing strategies (Longer service lifespan and MI reduction). **Paper II** also investigates these two strategies, albeit modelled in a different way, while also including the Substitution (narrowing strategy) [Figure 2].

The introductory essay of this thesis expands the scope of **Papers I** and **II** with the inclusion of Recycling (closing strategy) in the CE strategies covered (Figures 1 and 2). This is implemented by adding the current recycling process efficiency rates in each CE scenario investigated in **Paper II**, as well as adding a Recycling scenario that assumes that maximum recycling process efficiency rates are achieved in 2050. By doing so, I provide estimates for the primary demand and secondary supply of metals that together fulfil the gross metal demand (inflows). Appendix A of this introductory essay provides the methodology followed for the recycling analysis.

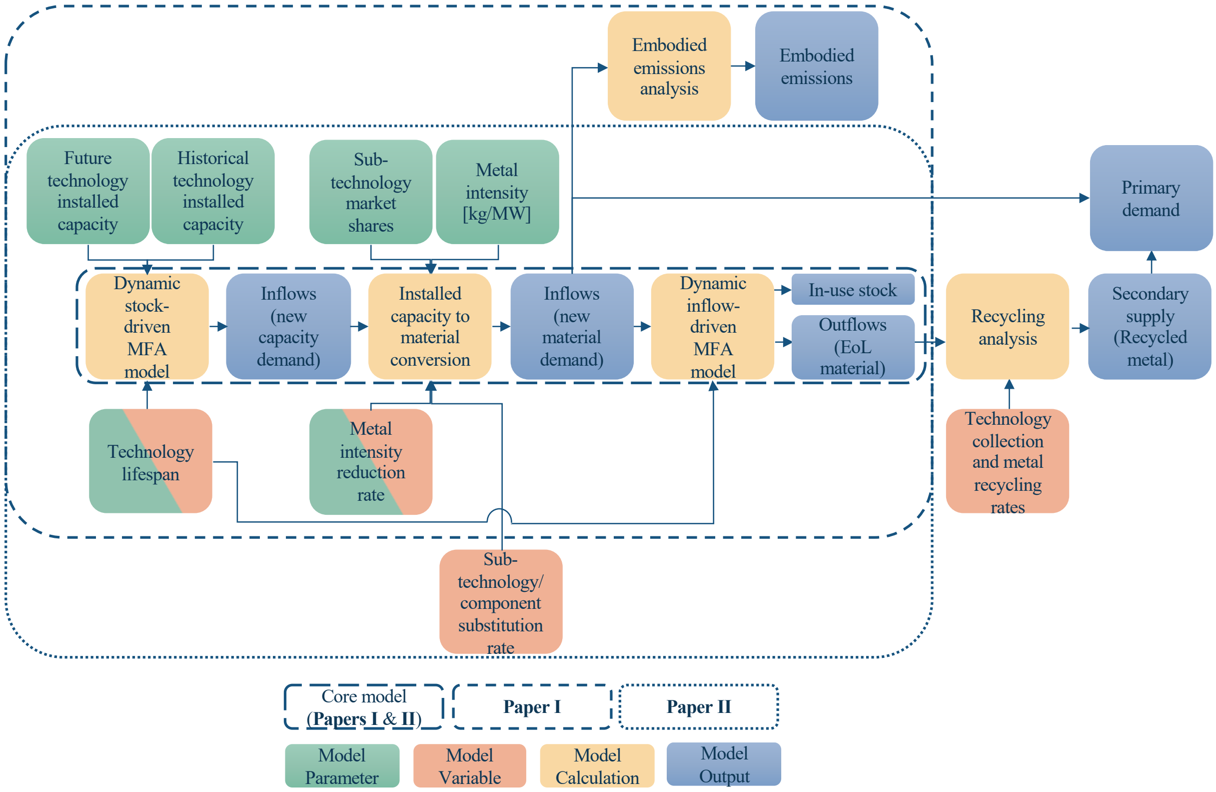

Figure 1: Graphical representation of the modeling framework of the introductory essay of the thesis, which includes the necessary components from the model frameworks presented in **Papers I** and **II**. Boxes shaded with both green and orange shading indicate input data that were used as parameters in **Paper I** and as variables in **Paper II**.

2.3 Scenario setting

For the presentation of the results based on the model of **Paper I**, in total I investigate the following four scenarios: Baseline scenario; Longer service lifespan scenario; MI reduction scenario; and Composite scenario. The main assumptions made for these scenarios are summarized in Table 3.

For the presentation of results based on the model of **Paper II**, in total, I investigate seven scenarios: Baseline scenario; Longer service lifespan scenario; MI reduction scenario; Substitution scenario; Recycling scenario; Composite scenario; and MI reduction, Substitution & Recycling scenario. Table 4 provides descriptions, including the main assumptions, of the scenarios.

For the results presented in this introductory essay based on the models from both papers, the Baseline scenario includes the wind and solar PV capacities as presented in the Swedish transmission system operator SvK's Renewable Electrification (RE) pathway [82] (Figure 3).

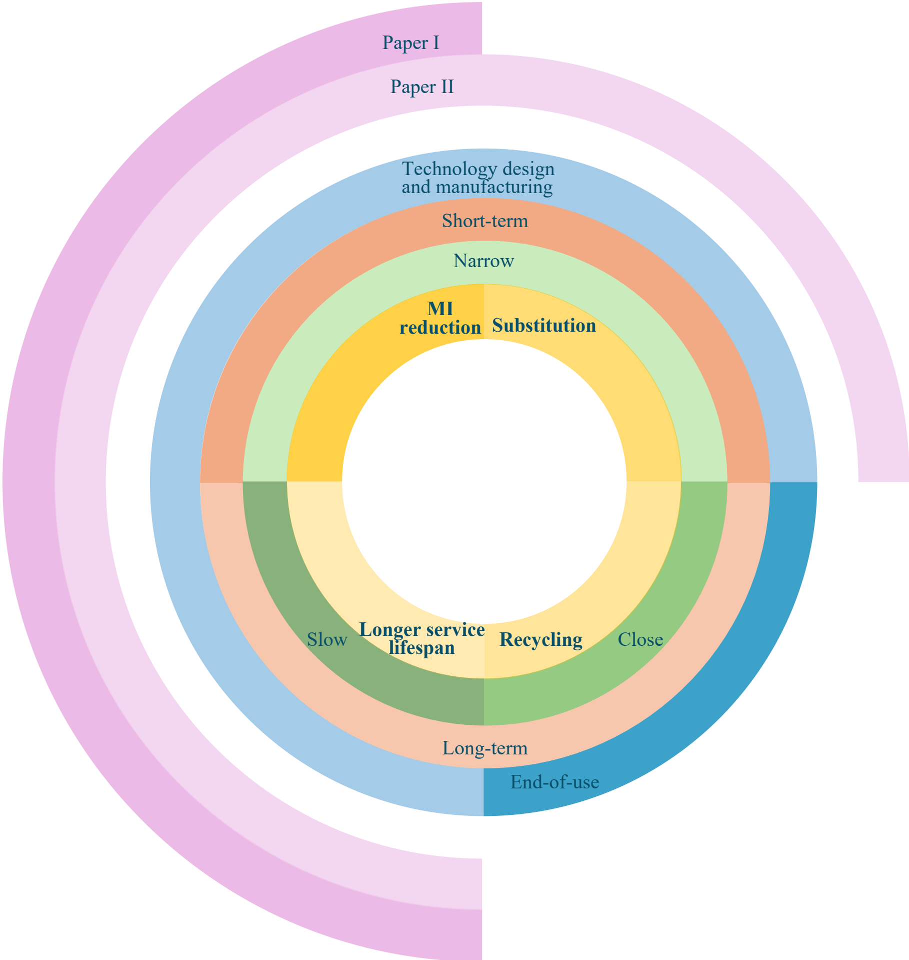

Figure 2: Circular economy strategies included in the introductory essay of the thesis (indicated by yellow shading) organized according to their effects on resource flows (Slowing, Narrowing and Closing) [green shading], their impacts in time for wind and solar PV technologies (short-term vs long-term) [orange shading], their stages throughout the wind and solar PV technology lifecycle (from technology design and manufacturing, to operation and maintenance, to end-of-use) [blue shading], and the extent of their coverage in the papers appended to this thesis (purple shading).

SvK provides alternative pathways set out to reach the national climate mitigation targets [82]. These were obtained in a collaboration with stakeholders from the industry, with the intention of identifying future needs and challenges for the electricity system. The Swedish Energy Agency (SEA) also publishes pathways for the decarbonization of the Swedish electricity system. The installed capacity data between SEA and SvK pathways differ substantially, especially in terms of the offshore wind over time. Our understanding is that these differences are due to the methodologies used by the respective agencies: SEA uses energy systems optimization modeling, while SvK uses a simulation analysis. The SEA results show a substantially lower installed capacity for offshore wind, reflecting the fact that current investment prices do not allow the optimization model to invest in offshore wind. Given that the aim focuses on the material dynamics of scenarios with high shares of VRE sources, we chose the SvK scenarios in order to be able to assess the large-scale deployment of wind power, including offshore wind, in addition to solar PV power. Yet, it should be stressed that the scenario used in this work should not be seen as a prognosis but used to illustrate a future with high share of VRE.

The SvK's RE pathway shows a steep increase in the electricity demand, from the current level of approximately 140 TWh to almost 300 TWh in 2050. In 2050, electricity production is dominated by large-scale offshore wind power, onshore wind power and solar PV power (Figure 3). The installed capacity of offshore wind increases substantially at a compound annual growth rate of 19% between 2021 and 2050, far exceeding the installed capacities of onshore wind and solar PV power by 2050.

Solar PV power also increases extensively, at an annual compound growth rate of 9% during the same period, while onshore wind, which saw a rapid increase since the 2000s, increases with a compound annual growth rate of 3% between 2021 and 2050 (Figure 3).

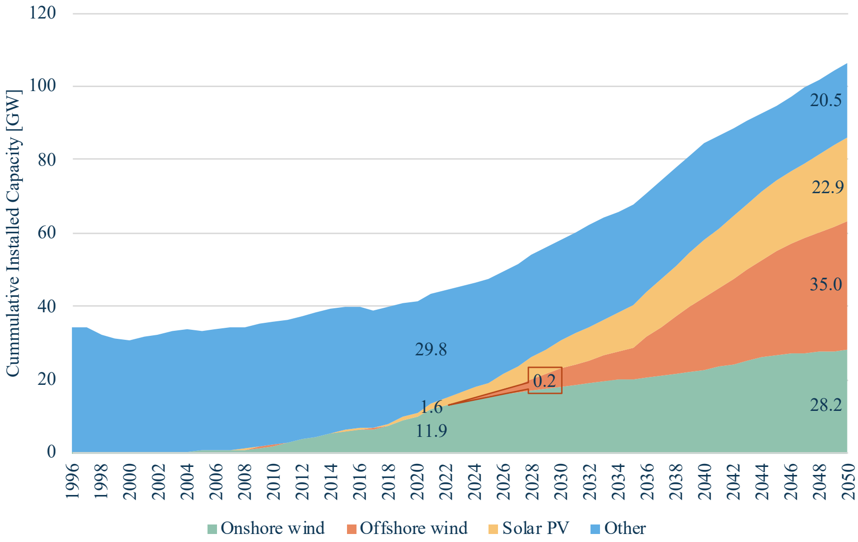

Figure 3: Cumulative installed capacities of onshore wind, offshore wind, solar PV, and the remaining (Other) electricity generation technologies during the historical (1996-2021) and scenario (2022-2050) periods for the Renewable Electrification (RE) pathway. This pathway is used in both of the papers appended to this thesis. Values for the base year (2021) and final scenario year (2050) are depicted.

Table 3: Scenario descriptions for the analysis based on **Paper I**. For more details refer to **Paper I**.

Scenario	Baseline	Longer service lifespan	MI reduction	Composite
Type of measure	The Renewable Electrification (RE) pathway from Swedish transmission system operator (SvK).	Longer service lifespan through improved technology designs	Reduced MI through improved technology designs	Assumptions under Longer service lifespan and MI reduction scenarios are combined
Lifespan assumption	No longer service lifespan assumed. Technology lifespan power kept constant at 20 years throughout the scenario period.	Discrete increase from base year (2021) lifespan value of 20 years to constant 30 years for onshore and offshore wind from 2022 and throughout the scenario period	Same as in Baseline scenario	Same as in Longer service lifespan scenario
MI reduction rate assumption	No MI reduction assumed. MI reduction rate kept constant at zero throughout the scenario period.	Same as in Baseline scenario	Linear increase to 10% reduction rates for concrete and steel applied based on literature averages for 2050.	Same as in MI reduction scenario
Embodied emission factors assumption	Two scenarios for the cradle-to-gate decarbonization of steel and concrete supply chains are provided: No emissions change and Transformative emissions change. In the no change, no reduction of emission factors is assumed. Current emission factors are kept constant throughout the scenario period. In the transformative change, emissions factors are assuming decarbonization measures from cradle-to-gate with the main ones being the hydrogen-based direct reduction for steel production, and alternative fuels (derived from wastes and biofuels) combined with carbon capture and storage in the cement industry. More details regarding the emission factors used can be found in **Paper I** and in the paper by Karlsson et al.[83]	Same as in Baseline scenario	Same as in Baseline scenario	Same as in Baseline scenario

Table 4: Scenario description analysis based on **Paper II**. Adapted from Table 2 of **Paper II** to include recycling. For more details refer to **Paper II** and Appendix A of the introductory essay of the thesis.

Scenario	Baseline	Longer service lifespan (Slowing strategy)	MI reduction (Narrowing strategy)	Substitution (Narrowing strategy)	Recycling (Closing strategy)	Composite (Slowing, Narrowing & Closing strategies combined)	MI reduction, Substitution & Recycling (MISR) (Narrowing & Slowing strategies) used only in Section 3.4
Type of measure	The Renewable Electrification (RE) pathway from Swedish transmission system operator (SvK).	Longer service lifespan through improved technology designs	Reduced MI through improved technology designs	Replaced metals through substitution by alternative designs of metals, components, or sub-technologies	Recovered metals contained in EoL technologies that have reached a waste treatment facility for further use	Assumptions made for Longer service lifespan, MI reduction, Substitution, and Recycling scenarios are combined	Assumptions made for MI reduction, Substitution, and Recycling scenarios are combined
Lifespan assumption	No longer service lifespan assumed. Technology lifespan power kept constant throughout the scenario period.	Linear increase from 2021 lifespan values (26.3, 21.7, and 23.6 years) to 40, 30 and 35 years for solar PV, onshore and offshore wind respectively by 2050	Same as in Baseline scenario	Same as in Baseline scenario	Same as in Baseline scenario	Same as in Longer service lifespan scenario	Same as in Baseline scenario
MI reduction rate assumption	No MI reduction assumed. MI reduction rate kept constant at zero throughout the scenario period.	Same as in Baseline scenario	Reduction rates per metal applied based on literature averages for 2050 and /or 2030.	Same as in Baseline scenario	Same as in Baseline scenario	Same as in MI reduction scenario	Same as in MI reduction scenario
Substitution rate assumption	No metal substitution rate assumed. Metal substitution rate kept constant at zero throughout the period	Same as in Baseline scenario	Same as in Baseline scenario	Linear increase to 20% and 50% substitution rates for solar PV and wind respectively by 2050	Same as in Baseline scenario	Same as in Substitution scenario	Same as in Substitution scenario
Collection rate assumption	Current collection rates (65% and 80% for solar PV and wind technologies respectively) kept constant throughout the period	Same as in Baseline scenario	Same as in Baseline scenario	Same as in Baseline scenario	Current collection rates (65% for solar PV and 80% for wind technologies) are linearly interpolated to potential collection rates (85% and 95%, respectively) between 2021 and 2050	Same as in Recycling scenario	Same as in Recycling scenario

Recycling process efficiency rate assumption	Current recycling process efficiency rates per metal kept constant throughout the scenario period.	Same as in Baseline scenario	Same as in Baseline scenario	Same as in Baseline scenario	Current recycling process efficiency rates increased to potential maximum rates between 2021 and 2050. Logistic curve was applied for materials that currently have close to zero recycling rates, and for the rest, linear increase.	Same as in Recycling scenario	Same as in Recycling scenario

3. Selected results and discussion

This chapter presents the results obtained from the research in the two papers appended to this thesis, as well as from the further analyses conducted for the thesis as described in the *Methodology*. Section 3.1 is based on the model and data from **Paper I** and addresses the Specific Aim *(i)* of this thesis. Sections 3.2 and 3.3 are based on the model and data from **Paper II**, as well as the additional recycling analysis conducted for this thesis. The address the Specific Aims *(ii)* and *(iii)* of this thesis. Section 3.4 addresses the Specific Aim *(iv)* of the thesis by presenting the results for the trade-offs between CE strategies, a topic that is discussed in both **Paper I** and **Paper II**. In similarity to Sections 3.2 and 3.3, it builds on the model and data from **Paper II**, together with the additional recycling analysis conducted in this thesis. Finally, Section 3.5 addresses the Specific Aim *(v)* of the thesis by discussing how the terminology used, the assumptions made on technology development, and the system boundaries established influence the modeling results, and/or the conclusions associated with the work of this thesis.

3.1 Impacts of CE strategies on embodied emissions

Paper I investigates the embodied emissions for steel and concrete by applying emission factors that were derived for steel and concrete from a supply chain perspective, covering from the raw material extraction to the production of the materials (cradle-to-gate). Karlsson et al. [83] provides such emission factors for the Swedish steel and concrete supply chains.

To estimate the impacts of the CE strategies on embodied emissions, the model from **Paper I** are run, providing results on the inflows for the CE scenarios of Longer service lifespan, MI reduction, and Composite, in addition to those for the Baseline scenario. For the emissions factors, two scenarios (just as in **Paper I**) are applied: No emissions change; and Transformative emissions change. As shown in Table 3, the No emissions change scenario assumes that currently used processes (i.e., blast furnaces for reducing iron from ore and conventional fossil fuel-reliant processes for cement clinker production) remain in place. Fossil-based fuels remain also for extraction and transports processes, although these emissions are minor in comparison to the process emissions. Both production processes produce emissions due to the chemical reactions involved, such that the average levels of process emissions remain constant. In the Transformative emissions change scenario, a reduction in extraction and transport emissions are assumed to be achieved by fuel changes and progressive electrification. A reduction in process emissions is assumed to be achieved by adopting technological innovations that are currently under development (for more on these assumptions see Table 3).

Eight scenarios are developed by combining the four CE scenarios (Baseline, Longer service lifespan, MI reduction, and Composite) with the two emission factors scenarios (No emissions change, Transformative emissions change). Figure 4 presents the cumulative and annual embodied CO_2e emissions for the eight scenarios, from steel and concrete needed for the wind turbines and their foundations for the period of 2022–2045, with 2045 being the year by which Sweden has committed to reducing GHG emissions to net-zero (and the last year for which emission factors are available from Karlsson et al. [83]).

On a cumulative basis (Figure 4a), the Longer service lifespan – No emissions change, MI reduction – No emissions change, and Composite – No emissions change scenarios, achieve emission reductions of 6%, 5%, and 10%, respectively, compared to the Baseline – No emissions change scenario. The reduction potentials compared to the Baseline – Transformative emissions change scenario are 3%, 4%, and 7% for the Longer service lifespan – Transformative emissions change, MI reduction – Transformative emissions change, and Composite – Transformative emissions change scenarios, respectively.

Considering the emission levels on an annual basis (Figure 4b), it is evident that in the absence of decarbonization strategies in the steel and concrete material production, and in the absence of CE strategies in the wind sector (i.e., Baseline - No emissions change scenario), the annual wind power embodied emissions in 2045 are 2.27 $MtCO_2e$. This constitutes an increase of 546% from the level in 2021, and is equivalent to 5% of the 2021 total national emissions of Sweden. As electricity generation becomes cleaner over time, in this scenario, the share of embodied emissions in wind technologies increases and eventually exceeds the electricity operational emissions by 2040.

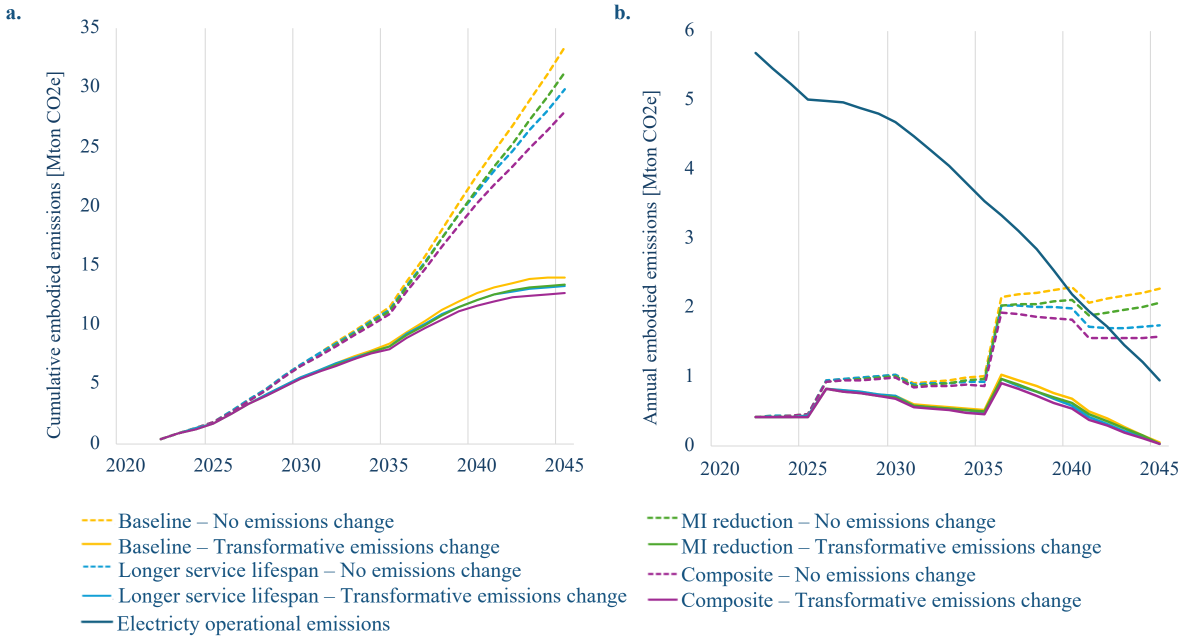

Figure 4: Embodied emissions related to the steel and concrete in wind turbines and their foundations per scenario on: a) a cumulative basis and b) an annual basis. The operational emissions of electricity generation include emissions from the Swedish electricity generation mix, taking into account electricity imports and exports [83] over the scenario period. The figure is based on results from **Paper I**.

CE strategies can reduce the annual emissions in 2045 by 24%, 9%, and 30% in the Longer service lifespan – No emissions change, MI reduction – No emissions change, and Composite – No emissions change scenarios respectively. In the Composite – No emissions change scenario this constitutes an increase in embodied emissions compared to 2021 of 382% and is equivalent to 3% of the total national emissions of Sweden in 2021. Compared to the Baseline - No emissions change scenario, the timepoint at which the embodied emissions exceed the electricity operational emissions is delayed by 3 years, occurring in 2043. In the Transformative emissions change scenarios, while the reduction potentials between the Baseline and the three CE scenarios persist (24%, 9%, and 30% in the Longer service lifespan – Transformative emissions change, MI reduction – Transformative emissions change, and Composite – Transformative emissions change scenarios respectively), the levels of embodied emissions are insubstantial, at between 0.06% and 0.08% of current national emissions.

Overall, the combination of Slowing (Longer service lifespan scenario) and Narrowing (MI reduction) CE strategies exhibits a strong potential to reduce both the annual and cumulative embodied emissions related to steel and concrete, during the energy transition period with large-scale deployment of wind power. Despite their role, emission reductions related to the cradle-to-gate processes, especially the production processes, of these materials are essential to for wind power to comply with Sweden's decarbonization target.

The source of the emission factors used, the paper of Karlsson et al. [83], provides four alternative emission factor pathways, each of which involves different emission reduction measures in the cradle-to-gate. In choosing emissions factors to apply in the MFA analysis, which involves CE strategies, one has to be careful to avoid double counting in a case in which CE strategy is also included in the emission reduction measures used to construct the emission factors. Indeed, Karlsson et al. [83] have presented several pathways, two of which include material efficiency as an emission reduction measure. Applying these pathways would result in double counting, given the MI reduction CE strategy is in my model. Therefore, we used the emission factors that assume no material efficiency, since this is included in my MFA model. It is important to note that double counting could also occur in those cases in which other CE strategies, such as substitution and recycling, are modeled. Indeed, recycling input rates are not included in the emission factors for concrete and construction steel by Karlsson et al. [83]. In any case, given that the model of **Paper I** did not include recycling, no double counting could be applied. However, in the introductory essay of this thesis EoL recycling is applied as a CE strategy. Overall, care should be taken when applying emission factors in MFA analyses that include CE strategies, to avoid double counting, and in case of recycling avoid challenges with different ways recycling can be modeled.

3.2 Impacts of CE strategies on primary demand

This Section, building on **Paper II**, investigates the impacts of CE strategies on the primary metal demand (for 11 minor metals) related to wind and solar PV technologies.

Paper II provides the cumulative gross metal demands (cumulative inflows) in the scenarios studied, along with their reduction potentials compared to the Baseline scenario (Table 3 in **Paper II**). In the introductory essay of this thesis, by adding the recycling analysis (see *Methodology* and *Appendix A*), estimates are provided for the primary demand and secondary supply of metals that together fulfil the gross metal demand (inflows).

Table 5 summarizes the projected cumulative primary demands for metals for the period of 2022–2050, given in metric tonnes (henceforth referred to as 'tons') per scenario and sub-technology, as well as the reduction potentials (indicated with colors) for the five CE scenarios compared to the Baseline scenario. The annual primary metal demands for the same period per scenario for the wind and solar PV sub-technologies are portrayed in Figure 5.

The impacts of the CE scenarios vary across the wind and solar PV technologies. For wind power, the CE scenario that yields the greatest reduction is the Substitution scenario for light rare earth elements (LREEs) Nd and Pr (Table 5, Figure 5a-b), whereas for heavy rare earth elements (HREEs) Dy and Tb (Table 5, Figure 5c-d) the Substitution and MI reduction scenarios show equal contributions. On a cumulative basis (Table 5), for the total REE metals, the reduction potentials are 4%, 12%, 25%, and 31% for the Longer service lifespan, Recycling, MI reduction, and Substitution scenarios, respectively. On an annual basis, for LREEs (Light rare earth elements) (Figure 5a-b), even though the Recycling scenario reduces the primary demand at a lower rate than the MI reduction scenario for most of the scenario period, its reduction rate increases toward the end of the scenario period, reversing the trend from 2046 onwards. For the solar sub-technologies, MI reduction is the CE scenario that has by far the largest potential for decreasing the cumulative and annual metal demands. For the other CE strategies, differences exist among the metals and along the scenario period. Cumulatively, the Longer service lifespan, Recycling, Substitution, and MI reduction scenarios result in total metal reductions of 3%, 6%, 13%, and 60%, respectively (Table 5). On an annual basis (Figure 5e-k), the Substitution scenario follows the MI reduction scenario with the second-largest reduction potential throughout the scenario period for all metals except Ag (Figure 5e) and Ge (Figure 5f). It follows the same trend for Ag and Ge until 2043 and 2041 respectively, but following these years, the Recycling scenario shows larger reduction potential. For Ge, the primary demand in the Longer service lifespan scenario also becomes lower than in the Substitution scenario from 2048 onwards. While the Longer service lifespan is the scenario with the weakest potential for both wind and solar PV technologies and for most of the scenario period, given the long lifespans of wind and solar PV technologies, the potential of this scenario would continue to increase beyond the scenario end-year. This is especially the case for offshore wind and solar PV, which in contrast to onshore wind are introduced later in the studied period (Figure 3).

Some of the CE scenarios lower the primary demands in a certain year in the scenario period under current demand levels for some metals, despite the large increase in the wind and solar PV installed capacity. For wind power (Figure 5a-d), no single CE scenario is sufficient to attain a primary demand that is lower than the current levels throughout the scenario period. However, a lower-than-current primary demand is achieved for all the REEs in the Composite scenario toward the end of the period. For the LREEs (Figure 5a-b), this is achieved from 2047 onwards and by 2050 it reaches 40% reduction compared to the current demand. The reduction in primary demand for HREEs (Figure 5c-d) reaches lower-than-current level from 2046 onwards, and by 2050, demand reductions of 84% and 85% are attained for Dy and Tb, respectively. For the solar PV power (Figure 5e-k), the MI reduction scenario alone leads to lower-than-current demand levels for Ag, Ge and Cd well before the end of the period; with this single scenario, lower-than-current demand levels are achieved for most of the scenario period for Ag and Ge, resulting in 80% and 56% reductions compared to current levels, respectively, by 2050 (Figure 5e-f).

The primary demand for Cd (Figure 5g) is reduced to lower-than-current levels in 2040 and reaches a 34% reduction by 2050. In the Composite scenario, the primary demands for Ag and Ge 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 (the following Section provides further information on the potential of the secondary supply). For Cd, the Composite scenario achieves a 68% reduction in the primary demand compared to its current demand level. For the remaining four metals (used for the CdTe and CIGS sub-technologies), lower-than-current primary demand levels are not achieved under any scenario throughout the period. Taken together, the results show that by implementing the MI reduction scenario, Ag has the strongest potential for reducing the annual primary demand than any other minor metal for the solar PV sub-technologies, followed by Ge.

Overall, while meeting the climate mitigation target, the Composite scenario shows that between 2022 and 2050, the CE strategies combined can cut by more than half the required cumulative primary demands for all the metals studied, as compared with the Baseline scenario (reductions of between 52% and 87%) [Table 5]. Ag, Cd, Ga show the highest cumulative reduction potentials, achieving reductions of more than 70%, and Ag, in particular, reaching an 87% reduction. On an annual basis (Figure 5), between the Baseline and Composite scenarios, for wind power, LREEs and HREEs achieve 90% and 97% reductions, respectively, in 2050. For solar PV metals, the reduction is in the range of 77%–117%. Therefore, the combination of Slowing (the Longer service lifespan scenario), Narrowing (the MI reduction and Substitution scenarios) and Closing (the Recycling scenario) CE strategies exhibits a strong potential to reduce both the annual and cumulative primary metal demands, and even eliminates the annual primary demand for some metals, during the energy transition period with large-scale deployment of VRE

Table 5: Cumulative primary demand for minor metals (in tons) for the period of 2022–2050, and the percentage reductions in the primary demands in the CE scenarios compared with the Baseline scenario.

The reduction potentials are classified as follows: up to 20% (dark orange); between 20% and 40% (light orange); between 40% and 60% (yellow); between 60% and 80% (light green); and between 80% and 100% (dark green). For wind power, the data are first provided for location (onshore & offshore) and sub-technology (DD-PMSG & GB-PMSG), and then for wind total (combining location & sub-technology). Source: **Paper II**, with additional analysis.

Technology	Sub-technology	Minor metal	Cumulative (2022-2050) primary demand in scenarios [tons]						Reduction in primary demand compared with the Baseline scenario [%]				
			Baseline	Longer service lifespan	MI reduction	Substitution	Recycling	Composite	Longer service lifespan	MI reduction	Substitution	Recycling	Composite
Wind (onshore & offshore)	DD-PMSG & GB-PMSG	Nd	5729	5494	4651	3933	5059	2725	4%	19%	31%	12%	52%
		Pr	1143	1096	928	785	1010	544	4%	19%	31%	12%	52%
		Dy	859	824	590	590	759	346	4%	31%	31%	12%	60%
		Tb	188	181	129	129	166	76	4%	31%	31%	12%	60%
Solar PV (distributed & centralized)	c-Si	Ag	857	822	185	757	757	116	4%	78%	12%	12%	87%
	a-Si	Ge	12.4	11.7	7.2	11.1	10.6	5.1	5%	42%	10%	15%	59%
	CdTe	Cd	92.4	91.1	27.5	80.0	90.3	23	1%	70%	13%	2%	75%
		Te	71.9	70.9	29.8	62.3	70.2	25.3	1%	59%	13%	2%	65%
	CIGS	In	19.8	19.3	9.8	17.1	18.9	8.0	2%	51%	14%	4%	60%
		Ga	7.4	7.3	2.5	6.4	7.1	2.1	2%	66%	14%	4%	72%
		Se	45.6	44.4	20.3	39.3	43.6	16.6	2%	55%	14%	4%	64%

Figure 5: Annual primary demand in tons per year for each scenario and minor metal used for wind (**a-d**) and solar PV (**e-j**) power in Sweden. Source: **Paper II**, with additional analysis.

3.3 Impacts of circular economy strategies on secondary supply

While neither of the appended papers estimates the quantities of recycled materials (secondary supply), both papers provide estimates of its potential. In **Paper I**, the potential secondary supply is estimated using an indicator called the *circularity potential*, which we define as the outflows divided by the inflows (see Table 2 in **Paper I**). In addition to the circularity potential indicator, in **Paper I** the inflows and outflows are plotted together to show the physical scale of the flows (see Figure 5 in **Paper I**). In **Paper II**, we refrain from using the term *circularity potential*, acknowledging that recycling is not included as a strategy in our study. Instead, we use the term *demand-supply metal balance*, which better represents what we show, 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 **Paper 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 **Paper II**).

In the introductory essay of this thesis, the quantity of the secondary metal supply (recycled metals) in Sweden that can contribute to fulfil the gross metal demand within the solar PV and wind power applications, as well as the remaining secondary supply that can cover metal demands in other applications, are estimated. Figure 6 shows for the Composite scenario the primary demand, the secondary supply needed to be used within the system, and the secondary supply that can be used for other applications.

For wind power (Figure 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 6a-b) and HREEs (Figure 6c-d) could be supplied from generating capacity that reaches its EOL in that same period. For solar PV, the secondary supply before the 2040s is also kept at negligible levels, with the exceptions of Cd and Te (Figure 6g-h). The latter metals already today have high collection and recycling process efficiency rates due Cd, ensuring that most of the metal is recycled rather than dissipated in the environment. The primary demands for Ag and Ge used in the c-Si and a-Si sub-technologies (Figure 6e-f) are eliminated from 2043 and 2046 onwards, respectively (as also shown in Figure 5e-f). The secondary supply levels from solar PV 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 Ag, 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 Ge, the remaining supply for other applications remains lower than the secondary supply needed within the system. For Cd and Te 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 In, Ga, and Se, respectively.

Overall, the Composite scenario shows that towards 2050, the CE strategies combined can substantially increase the secondary supply potential towards the end of the scenario period. For wind power (Figure 6a-d), the combined CE strategies exhibit a strong potential to increase the secondary metal supply, with potentials in the range of 56%–72% in the last 5 years of the scenario period. For solar PV power (Figure 6e-k), the magnitude of the secondary supply potential during the same period depends largely on the sub-technology. Full potential to fulfil the gross demand through the secondary supply is achieved with c-Si (Ag) and a-Si (Ge), with the remaining supply used for other applications. For CdTe, the secondary supply ranges between 42% and 56% of gross demand, while for CIGS the secondary supply share of the gross demand is in the range of 13–18%.

While the findings show that by 2050 the secondary supply can cover more than half of the gross metal demand for all the REEs (Nd, Pr, Dy, Tb) and for Ag, Ge, and Cd in Sweden, the results are similar to those reported in previous studies that have used dynamic MFA of wind and solar PV applications, pointing to the limited potential of recycling in the short-term [69], [74], [84], [85]. 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. With the exceptions of Ag and Ge, the results indicate that the primary demand is required throughout the scenario period for all the remaining metals. This suggests that in order to meet decarbonization targets in scenarios of large-scale deployment of wind and solar PV power, there is a need to expand metal production.

Figure 6: Primary demands and secondary supply levels in tons per year for each metal used in wind (**a-d**) and solar PV (**e-k**) power in Sweden in the Composite scenario. The secondary supply is divided into the secondary supply secondary supply needed to be used within the system, and the remaining secondary supply that can be used for other applications. Source: **Paper II**, with additional analysis.

3.4 Trade-offs between circular economy strategies

Papers I and **II** investigate the impacts of CE strategies in terms of the inflows (gross demand) and outflows. Here, given the recycling analysis introduced in the introductory essay, we estimate the impacts of the CE strategies on the primary demand and secondary supply.

Figure 7 shows the primary demand and secondary supply under the following three scenarios: Recycling scenario; MI reduction, Substitution & Recycling scenario (MISR); and Composite scenario. The Recycling scenario consists of the Closing strategy. The MI reduction, Substitution & Recycling scenario consists of the Narrowing and Closing strategies combined, and the Composite scenario consists of the Slowing, Narrowing and Closing strategies combined. In an ideal case, all of the gross demand could be met by the secondary supply, closing the resource loops and, thereby, eliminating the need for the primary demand, which is generally associated with higher supply-chain environmental impacts [86].

Figure 7 shows that the secondary supply availability (dotted lines) decreases progressively from the Recycling scenario (Closing strategy) with the addition of the Narrowing strategy (MISR scenario) and Slowing (Composite scenario) strategies [for better resolution of the secondary supply availability, see Figure B1 in Appendix B]. The reductions are in the ranges of 17%–45% and 37%–62% across the metals for the MISR scenario and the Composite scenario, respectively. This reduction of the secondary supply from the Recycling scenario to the MISR scenario reveals a trade-off between the primary demand and secondary supply availability: as the material intensities of the sub-technologies decrease over time, not only the primary demand decreases, but also the level of availability for the secondary supply. Still, the reduction of the primary demand between the two scenarios is much greater than the reduction of the secondary supply, which justifies the net-positive impact of the Narrowing and Closing strategies combined, as opposed to the Closing strategy alone. Looking at Nd (Figure 7a), for example, secondary supply over the scenario period is reduced by 17% in the MISR scenario compared to the Recycling scenario. However, the primary demand during the same period is reduced at a substantially higher level, by 47%.

Regarding the Composite scenario, however, a new trend arises. The Composite scenario has a lower secondary supply availability than the MISR scenario, which means that it has the lowest potential of the three scenarios. Indeed, as we point out in **Papers I** and **II**, in any given year, the Narrowing and Slowing strategies together reduce outflows compared to the Narrowing strategies alone. This is because Slowing strategies shift outflows in time, reducing their reduction potential during the scenario period. However, at the same time, Narrowing and Slowing strategies reduce inflows, and they do so at a lower rate than they reduce outflows, making their outflow to inflow ratio (**Paper I**) lower or their difference (demand-supply balance) [**Paper II**] larger. In this introductory essay, we show that this results in a lower primary demand for the Composite scenario compared to the MISR scenario. Overall, combining the Slowing strategy (Composite scenario) with the Narrowing and Closing strategies increases the primary demand while reducing the secondary supply. Therefore, the MI reduction, Substitution & Recycling scenario is preferred, both in terms of primary demand reduction and secondary supply increase, as compared with the Composite scenario.

To contextualize further this observation, Figure 8 shows the gross demand, the primary demand, and the secondary supply per metal under two scenarios: the MISR scenario, which combines the Narrowing and Closing strategies; and the Composite scenario, which combines the Slowing, Narrowing, and Closing strategies. It shows that combining the Slowing, Narrowing and Closing strategies (Composite scenario) reduces the gross demand compared to using the Narrowing and Closing strategies only (MISR). However, this reduced gross demand is fulfilled by a higher primary demand and lower secondary supply, as compared to the Narrowing and Closing scenario, as shown in Figure 7. Therefore, during the scenario period, using the Slowing strategy (Longer service lifespan) in combination with the

Narrowing and Closing strategies creates a trade-off between the objective of reducing gross demand on the one hand, and reducing the primary demand and increasing the secondary supply on the other hand. This is a recent finding, and further research is needed before definitive conclusions can be drawn on the interactions between CE strategies over time. The following section provides some reflections on this issue.

The MISR scenario is omitted from the presentation of the results in Sections 3.1 to 3.3, despite showing a lower primary demand and a higher secondary supply availability. The reason for this is that the goal of these sections is to show the potential of all the strategies combined, rather than the optimal potentials, especially given that in reality, these strategies are all applied together (despite the trade-offs that I discuss here).

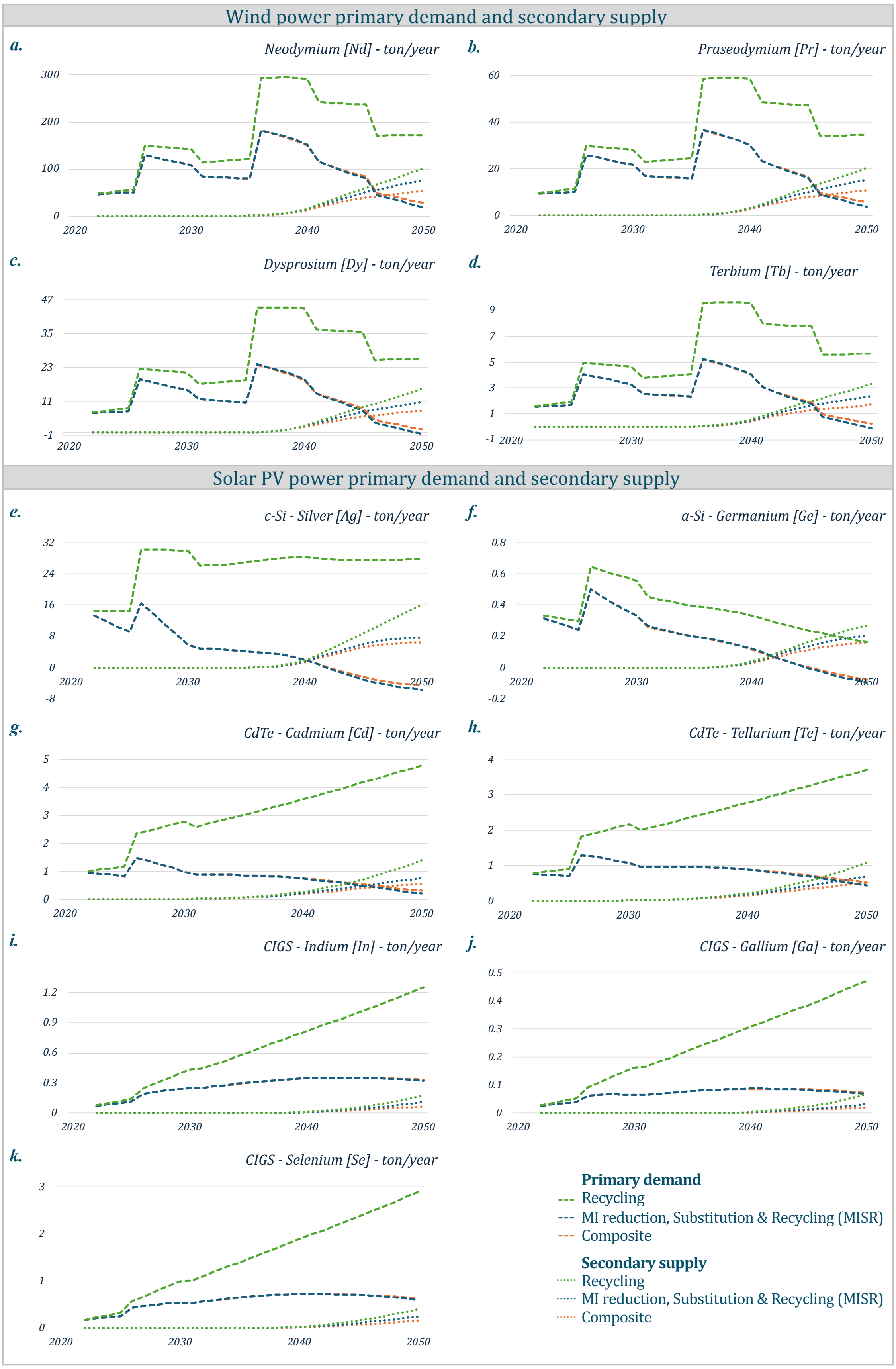

Figure 7: Primary demand (dashed lines) and secondary supply (dotted lines) in tons per year for each metal for wind (**a-d**) and solar PV (**e-k**) power in Sweden in the Recycling scenario (Closing strategy), MI reduction, Substitution & Recycling scenario (MISR) [Narrowing and Closing strategies], and Composite scenario (Slowing, Narrowing and Closing strategies). Source: **Paper II**, with additional analysis.

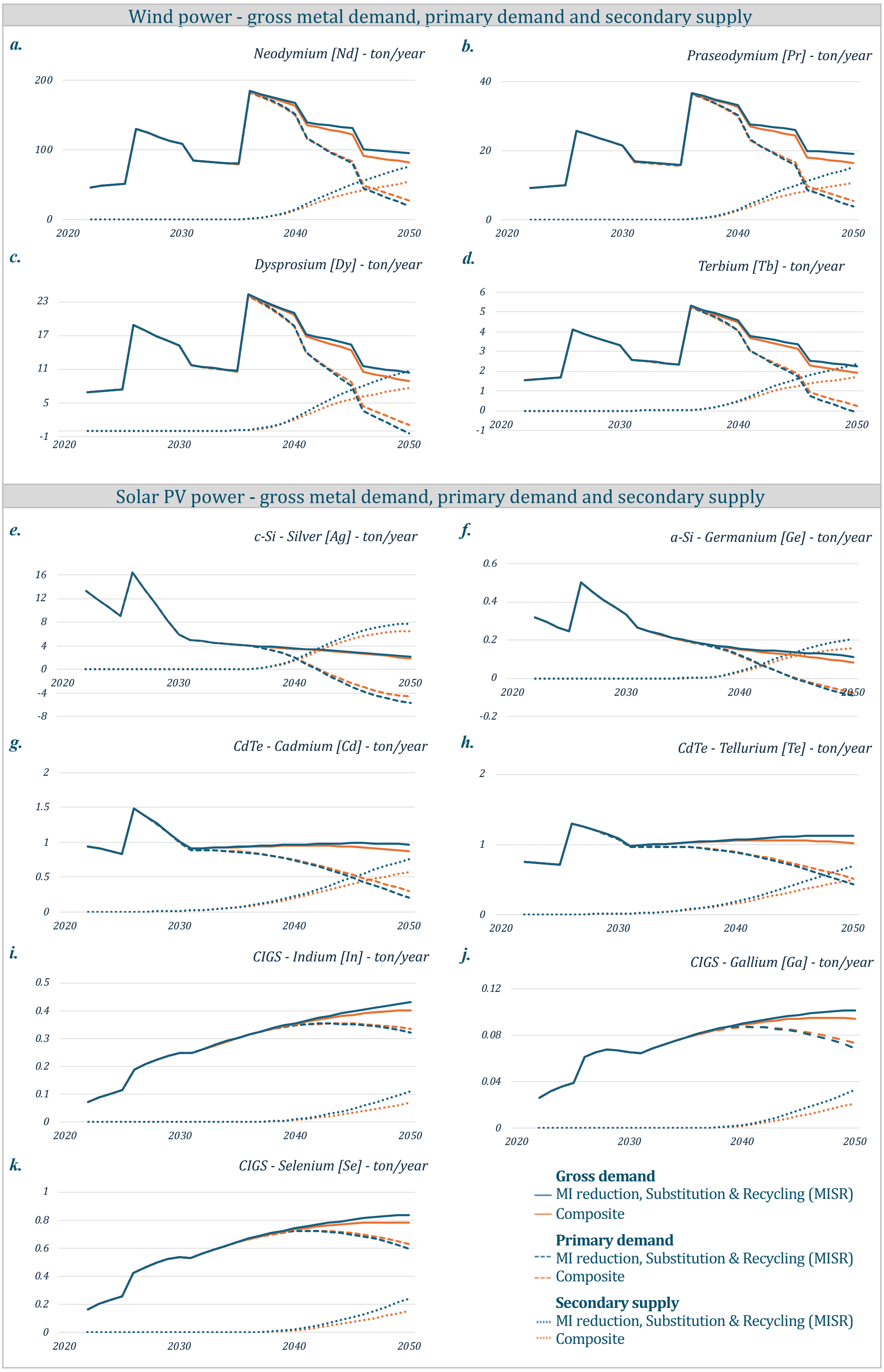

Figure 8: Gross demand (solid lines), primary demand (dashed lines) and secondary supply (dotted lines) in tons per year for each metal for wind (**a-d**) and solar PV (**e-k**) power in Sweden in the MI reduction, Substitution & Recycling (MISR) scenario and the Composite scenario. Source: **Paper II**, with additional analysis.

3.5 Discussion on terminology, technology development assumptions, system boundaries, and methodology

This section discusses the terminology used, technology development assumptions made, system boundaries established, and methodological choices in the work of this thesis, and how they influence the modeling results, and/or the conclusions associated with the work.

Terminology

- “Critical and bulk materials”

Paper I included four materials: concrete, steel, neodymium and dysprosium. To characterize these materials, the term *bulk and critical materials* was used, with *bulk* referring to concrete and steel, and *critical* referring to neodymium and dysprosium. Though the term *bulk and critical materials* is used in the literature in a similar manner (e.g.,[11]), this term can be questioned because the *bulk* and *critical* terms belong to two different categories: the term *bulk materials* is a characterization based on a physical category that is stable over time and not context-dependent, while the *critical materials* category is usually based on economic importance and supply risk, both of which are dynamic and context-dependent. In other words, bulk materials would be bulk no matter the time and geography. However, critical materials are not critical in themselves. Therefore, while neodymium and dysprosium were, at the time of publication, deemed to be ‘critical’ in the critical raw material lists for several geographic areas (EU, Australia, Japan), and still are, this may change in the future. A more accurate term for these metals might be *minor metals* or *rare earth elements*.

- “Circularity potential”

In **Paper I**, we use the term *circularity potential* for an indicator of outflows divided by inflows. While it is used in the literature [60] in this way, going forward a more-precise terminology is appropriate, since the *circularity potential* term is not well defined in the literature, and therefore used with different meanings [60], [87]. Indeed, as also mentioned in Section 3.3, in **Paper II**, after multiple rounds of different forms of terminology that could be used for the difference between inflows and outflows, we decided to refrain from the use of *circularity potential*, and instead we used *demand-supply balance*, which better represents what we quantify.

- “Clean energy technology” vs “low-carbon technology”

In **Paper I**, we use the term *clean energy technology* to refer to renewable energy technologies and electric vehicles. The use of the term *low-carbon technology* is deemed more to be accurate for describing these technologies, considering that while these technologies reduce GHG emissions, they are associated with other social and environmental impacts, as discussed in the *Introduction*.

- “Primary material” vs “virgin material”

In my work, I make a deliberate choice to use the term “primary” instead of “virgin” to refer to materials. The term "virgin" has indeed been critiqued for its potential sexist connotations. Critics argue that the term can reinforce gendered stereotypes, even in contexts unrelated to human sexuality, such as material science or industry. The main critique is that the term "virgin" implicitly ties the concept of purity and value to a term historically associated with women's sexual status. This connection, while likely not intended in scientific and industrial contexts, can subtly reinforce gendered stereotypes and values that are increasingly recognized as problematic.

Technology development assumptions

- Fixed vs dynamic material intensity over time

In the sensitivity analysis conducted in **Paper I**, a fixed material intensity is tested. While several studies have used a fixed intensity (see Table 1), the dynamic representation of material intensity over time is important given the material intensity reductions observed in past years and that are expected to continue. Therefore, a better approach would be to assess a low and a high material intensity reduction over time.

- Choice of collection and recycling rates

Depending on the research question being investigated, the scope of the recycling process can relate to the recycling efficiencies at a product's EoL or the recycling efficiencies in metal production. According to Graedel et al. [88], recycling efficiencies at a product's EoL include the collection, process efficiency, and EoL recycling rate, while the recycling efficiencies in metal production include the recycling input rate, recycled content, and old scrap ratio. In our analysis, building on the model described in **Paper II** (as presented in Sections 3.2, 3.3, and 3.4), we have opted for the recycling efficiencies at a product's EoL. In particular, applying the definitions of Graedel et al. [88], we have collected data for two processes that are relevant to the recycling efficiencies at the EoLs of wind and solar PV sub-technologies: 1) the old scrap collection rate; and 2) the recycling process efficiency rate (focusing on functional recycling, which refers to the process whereby the metals in a decommissioned technology are separated and sorted to obtain recycled content that is returned to raw material production processes). Based on Graedel et al. [88] definitions, the old scrap collection rate reflects the quantity of the EoL metal contained in decommissioned technologies that is collected and enters the recycling chain. The recycling process efficiency rate is the efficiency of any given recycling process, also referred to as the *recycling yield* or *recovery rate*.

Moreover, 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. We have gathered data for the recycling process efficiency rate (see Appendix A), which measures the proportion of material in waste flows that is recycled from the solar PV and wind sub-technologies.

In the literature, various data on the rates related to the recycling process and a broad range of values are documented. The discrepancies related to the reported recycling rates of metals in the literature can be attributed to differences in: definitions (EoL recycling rate, recycling input rate, etc.), geographic scope, time periods studied, product focus, and technological advances. Furthermore, some studies use the term *recycling rate* to designate the ratio between the primary material entering a recycling facility and the useable secondary material produced by the recycling process, i.e., the recycling process efficiency rate, as defined above. However, other studies use the same term to include also other efficiencies related to the recycling process such as collection rate [89]. Therefore, when comparing rates and collecting data for the recycling process from different studies, it is essential to consider these factors to understand the contexts and implications of the reported values.

System boundary

- Technology and material space

Paper I assesses the wind-related material dynamics in the following pathways: Decentralized renewable, Dispatchable electrification, and Renewable electrification. It shows that there are substantial differences between the three scenarios (for more details on the assumptions made regarding the wind capacity data in each scenario, refer to the *Supplementary material* of **Paper I**), especially between the Decentralized renewable and the Renewable electrification pathways, with the latter showing the highest demands for the REEs neodymium and dysprosium. While this is the case in the technology system boundary of our study, it is important to bear in mind that given the importance of REE usage in other applications that are crucial for decarbonization, such as electric vehicles, the trend observed in our analysis could change substantially if the system boundaries are expanded to include other clean technologies. Indeed, in the Decentralized renewable scenario, a high degree of sector integration between the transport and electricity sectors takes place, and several variation management techniques are implemented to provide flexibility. Another key application that utilizes REEs, such as neodymium and dysprosium, is in electric and electronic equipment. Therefore, the parallel developments of the energy and digital transitions are expected to increase demands for certain metals. The material dynamics of wind and electric vehicles [67], as well as of the energy and digital transitions [62], [67] have recently gained attention.

In our analysis, we investigate the potential for substitution potential with novel technologies for wind and solar PV power for the Swedish electricity system. While these novel technologies eliminate the minor metals that are currently used in wind and solar PV applications, they introduce new metals associated with new trade-offs. For wind power, high-temperature superconducting (HTS) generators, which can substitute for PM-containing sub-technologies, may have higher efficiencies than REE-based PM wind turbines but utilize yttrium-barium-copper oxide magnets [90]. Yttrium and baryte (one of the most-common minerals of barium) are included in the EU's critical raw materials list and copper is included in the EU's strategic raw materials list [91]. Another potential substitute for REE-containing PM in wind power are ferrite-based PM. While they offer a cost-effective and readily available alternative to rare earth magnets, they have lower magnetic strength, greater size and weight, and potential limitations as to performance. The perovskite solar technology, which has achieved over 25% efficiency in laboratory settings, contains lead, which although it is not included in the EU critical or strategic raw material lists, poses significant environmental and health risks [92].

Therefore, while in our analysis the system boundary 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. Overall, the choice between current and novel technologies involves balancing the associated trade-offs. Research studies can investigate the potential trade-offs linked to these substitution options in terms of the supply risk, and the social, environmental and economic impacts.

- Temporal

Given the lifespans of wind and solar PV technologies (see Table 4), expanding the temporal boundary to include longer scenario timeframes (post-2050) would enable an analysis that includes the full lifecycle of the technologies commissioned during the initial scenario period, and capture the impact of Longer service lifespan scenario in a more comprehensive way. Furthermore, as I show in Section 3.4, there is a trade-off between the objective of reducing the gross demand on the one hand, and reducing the primary demand and increasing secondary supply on the other hand when the Slowing strategy (Longer service lifespan) is implemented together with the Narrowing and Closing strategies during the scenario period. This is a finding from the work conducted for this introductory essay (not included in the appended papers), and further research would be needed before drawing more firm conclusions. For example, to understand further the interactions between the Slowing, Narrowing and Closing strategies, and their impacts on the primary demand and secondary supply, it is important to study their impacts beyond the scenario period, after which the effects of both the Longer service lifespan and Recycling scenarios are expected to increase, whereas the rapid increase in the installed capacities of VRE technologies may slow down, following the achievement of decarbonization target. My findings raise new research questions: *At which point in time is the trade-off observed eliminated or reversed?* and *Under which conditions would this occur?* Understanding further the temporal dynamics of this trade-off could provide important information for actors in the supply chain of VRE technologies in terms of which strategies are more effective to prioritize, and when. For such decisions, however, my research, which focuses on the material dynamics would need to be complemented with analyses of the environmental impacts of the different strategies at hand.

- Geographical scope
    - Global vs national

Global MFA studies, such as those presented in Table 1, focus on broad, systemic issues that affect multiple countries and regions, such as global resource availability, international trade, environmental impacts, and global policy needs. The research questions explored often aim to understand the global implications of material flows and how international cooperation can be enhanced to support sustainable practices in relation to wind and solar PV power. In contrast, national MFA studies, such as the Swedish studies appended to this thesis, as well as the ones presented in Table 1, have their bases in the specific needs, challenges, and opportunities within a single country, and how can these be generalized and relevant to other countries. They typically address how the country can manage its resources, develop its industry, and meet national policy goals related to wind and solar PV deployment. Their research questions often aim to understand material flows at the national level, as well as to reduce environmental impacts and enhance domestic economic and resource security. By integrating the findings from both global and national perspectives, a more comprehensive and effective approach to sustainable resource management and renewable energy deployment can be achieved, ensuring that local actions contribute meaningfully to global sustainability goals.

- National vs national

During the past year, I have had the opportunity to collaborate with a fellow Cypriot on a study looking into the material dynamics of the solar PV transition in Cyprus. Unlike Sweden, Cyprus, an island country, currently has low shares (15%) of renewable electricity in its electricity mix [93]. Furthermore, in Cyprus, 78% of the currently installed renewable capacity comes from solar PV, and Cyprus' electricity transition is heavily reliant on this single technology, given its strong potential for solar PV power and its low potentials with respect to other renewable electricity sources. During this collaboration, it became evident that the local context shapes the approach to MFA, necessitating the tailoring of our studies to address the specific challenges and opportunities present in the country in focus. For example, differences in solar resource potential, national energy strategies, economic and industrial contexts, and geographic and environmental considerations (such as land use and land availability) shape the research scope. For instance, in **Paper II**, our research indicates that the continued dominance of crystalline silicon (c-Si) is preferable from the minor metal circularity perspective, assuming the availability of an adequate recycling capacity for Ag. However, for a country that is heavily reliant on solar PV such as Cyprus, diversification of sub-technologies may be of greater importance from the security of supply perspective.

Methodology

- One-to-one replacement between the primary demand and secondary supply

In the work conducted as part of this introductory essay, secondary supply availability was modeled to replace the primary demand on a one-to-one basis. The assumption underlying this decision is that once metals are recycled back to their elemental forms, their chemical properties are not changed, and they are therefore used for new production. While technically this is sound, as demonstrated previously [36], [37], one-to-one replacement is not a rule due to the risk of rebound effects on the demand. Indeed, one study [36] has unpacked the impact of recycling on the primary demand and suggests strategies to avoid the rebound effect.

4. Conclusions

This thesis, entitled *Matter matters*, is focusing on the material implications of decarbonization pathways. Using Sweden as a case study, the work investigates the material dynamics associated with wind power and solar PV technologies in a pathway that entails a high level of electrification driven by large-scale deployment of wind and solar PV power. It provides insights into the potential for reducing embodied emissions related to bulk materials, through CE strategies that focus on technology design improvements (lifespan expansion, MI reduction). Furthermore, it provides insights on the potential, and trade-offs, for reducing primary demand and increasing secondary supply availability for minor metals through CE strategies that span the spectrum of Slowing (Longer service lifespan scenario), Narrowing (MI reduction, substitution scenario) and Closing (Recycling scenario) CE strategies.

Related to Specific Aim *(i)* of this thesis, I show that, for embodied emissions, if neither technological innovations to decarbonize cement and steel supply chains nor CE strategies in the wind power sector are adopted, the embodied emissions related to these bulk materials in wind power turbines and their foundations could increase by 546% by 2045 (the year by which Sweden has committed to reducing GHG emissions to net-zero), as compared to current emissions levels. This is equivalent to 5% of current total national GHG emissions. The Slowing and Narrowing CE strategies related to technology design improvements (Longer service lifespan and MI reduction combined) have the potential to reduce that level by 30%, resulting in a 382% increase compared to current emissions levels. Therefore, while these CE strategies can play important roles in reducing the required scale of decarbonization in the supply chains of these materials, reductions related to the cradle-to-gate processes, especially the production processes, are still essential for wind power to comply with Sweden's decarbonization target. Embodied emissions related to the materials in VRE technologies warrant greater attention in terms of strategies aimed at mitigating climate change and sustainable resource use, including for example, investigations of additional CE strategies.

In terms of the impacts of CE strategies on the primary minor metal demand for wind and solar PV applications, i.e., Specific Aim *(ii)* of this thesis, I show that the Narrowing strategies (MI reduction and Substitution scenarios) have the strongest impacts on the primary demand reduction over the scenario period. MI reduction, in particular, exerts by far the strongest impact of the CE strategies studied in terms of solar PV power (resulting in total reductions in the range of 42–78% for metals by 2050 as compared with the Baseline scenario which assumes no CE strategies). For wind power, depending on the metal, the MI reduction and/or Substitution scenarios have the highest potential to reduce primary demand by 2050, with reductions ranging between 19% and 31%. In the absence of Slowing and Narrowing CE strategies, i.e., the Recycling scenario (Closing strategy only), the results show that if the maximum collection and recycling process efficiency rates are achieved by 2050 for wind power and solar PV EoL management, 12% of the primary REEs used in wind power and 10% of the primary minor metals used in solar PV could be avoided by 2050, thereby reducing the lifecycle impacts compared with primary metal production. This quantity, however, decreases when the Slowing and Narrowing strategies are introduced together with the Closing strategy, resulting in 7% and 6% reductions for wind and solar PV power, respectively, in the Composite scenario, as compared with the Baseline scenario (a finding that addresses Specific Aims *(ii)* and *(iv)* of this thesis). The Slowing strategy studied (Longer service lifespan scenario) shows the lowest potential, although its impact is expected to increase post-2050.

Furthermore, in accordance with Specific Aim *(ii)* of the thesis, I show that while achieving the climate mitigation target, the Composite scenario can cut the required cumulative primary demands for all metals studied by between 52% and 87%, as compared with the Baseline scenario. On an annual basis, the reduction potentials are in the ranges of 90%–97% for wind power and 77%–117% for solar PV power. Therefore, during the energy transition period with large-scale deployment of VRE, the combination of the Slowing, Narrowing and Closing CE strategies exhibits strong potential to reduce both the annual and cumulative primary metal demands, and even to eliminate the annual primary demand for 2 (Ag, Ge) of the 11 minor metals studied. Overall, implementation of the Slowing, Narrowing and Closing CE strategies is crucial for conserving minor metals, reducing the burden on present reserves of such metals, and diminishing the social and environmental impacts associated with their primary extraction.

Still, with the exceptions of Ag and Ge, my results indicate that a primary demand is required throughout the scenario period for all the remaining metals. Therefore, the results show that while establishing effective and sustainable CE strategies is important, during the energy transition with high shares of VRE it is imperative to invest in demand reduction measures and ensure responsible mining practices.

Related to Specific Aim *(iii)* of this thesis on the combined impact of CE strategies on the secondary supply availability of minor metals, the analysis shows that sub-technology choices for solar PV are key determinants of the secondary supply potential. The secondary supply fulfils all the gross demand towards the end of the scenario period for Ag (c-Si) and Ge (a-Si), with the remaining supply for other applications. For CdTe, the secondary supply ranges from 42% to 56% on average of the gross demand in the last 5 years of the scenario period. For CIGS, the secondary supply share of the gross demand is lower than for the other sub-technologies, in the range of 13%–18% on average during the same period. For wind power, while the secondary supply does not fulfil the gross demand for any REE in the Composite scenario, it fulfills a large share of the gross demand, in the range of 56%–72% on average, during the last 5 years of the scenario period. While my findings show that by 2050, the secondary supply can cover more than half of the gross metal demand for all of the REEs, Ag, Ge, and Cd, my results point to the limited potential of recycling in the short-to-medium term stages of the energy transition for wind and solar PV technologies.

One of the main contributions of my work is the inclusion of the Slowing CE strategy, given that strategies to slow resource loops have received much less attention from researchers than strategies for Closing and Narrowing resource cycles [54; see Table 1]. In studying the Slowing strategy together with the Narrowing and Closing strategies, I identify a trade-off between reducing the gross demand on the one hand and reducing the primary demand and increasing the secondary supply on the other hand, thereby addressing Specific Aim *(iv)* of this thesis. The results show that combining the Slowing, Narrowing and Closing strategies (Composite scenario) reduces the gross demand compared to the Narrowing and Closing strategies alone (MI reduction, Substitution & Recycling scenario). However, this reduction is achieved at the expense of a higher primary demand and lower secondary supply. Exploring these dynamics beyond the scenario period can provide important insights into the interactions between the Slowing, Narrowing and Closing strategies.

As demonstrated in the work of this thesis, investigating the linkages between the material and energy dynamics of the energy transition can offer valuable insights into the synergies and trade-offs present in climate and natural resource policies. These insights can support governmental and industrial decision-making processes during the transition to a low-carbon and circular economy. In particular, the results of this work are relevant for actors along the supply chains of wind power and solar PV technologies. Such actors include those involved in the extraction of primary materials, the production of sub-technologies and their components, the recycling industry, and the electricity sector. Thoroughly tracking the progress of these and other CE strategies, along with investigating opportunities across all stages of the supply chain, is crucial.

5. Future work

Three possible directions for the work presented in this thesis are suggested below, along with some initial reflections of how they can be addressed. The first two are closer to my research interests.

1. Additional demand-side, and circular economy, strategies

Climate change and its impacts, driven primarily by the use of fossil fuels, motivate a transition away from fossil fuels primarily through the use of renewable electricity and the electrification of end-use sectors, such as transport, and industry. These supply-side mitigation strategies reduce GHG emissions, and thereby, the impacts of climate change. However, the extraction of materials and waste flows associated with low-carbon technologies will create social and environmental impacts on the local and global scales.

To this end, strategies that focus on the demand-side can reduce substantially both the magnitude of the climate challenge and the associated material requirements. These approaches lower energy consumption and associated GHG emissions, directly mitigating climate risks and reducing the magnitude of the decarbonization efforts required. In addition, they can reduce the environmental impacts of material use through Narrowing strategies and can support circular material flows through Slowing and Closing strategies.

In this thesis, three demand-side CE strategies related to technology design and the manufacturing stage of the technology lifecycle were investigated (Longer service lifespan – slowing strategy; MI reduction, and Substitution – Narrowing strategies), as well as a strategy at the end-of-use stage of technology lifecycle, i.e. Recycling (Closing strategy). While in this thesis I studied the impact of one Slowing strategy (Longer service lifespan scenario), future research could explore the implications of Slowing strategies related to the operation and maintenance stages of the technology infrastructure, such as lifespan extension, reusing, and remanufacturing. Indeed, impacts from demand-side CE strategies to slow resource loops through extending the lifespans of commissioned wind and solar PV technologies, reuse, repair, and remanufacturing have, thus far, received much less attention than other strategies. Permanent magnets, for example, have a useful lifespan longer than wind turbines [94], and they have the potential to be reused, thereby reducing the lifecycle impacts compared with primary REEs. Assessing additional Slowing CE strategies would extend the work that I have started on assessing the trade-offs between Slowing, Narrowing, and Closing strategies. To this end, assessing the impacts of CE strategies beyond the current scenario period might offer valuable insights into the interactions between CE strategies after the rapid expansion of wind power and solar PV power.

Furthermore, future work could investigate additional demand-side strategies. These strategies can be applied directly or indirectly, through the interconnections between the VRE (supply) and demand sectors, such as mobility and buildings to reduce material requirements.

For example, strategies that directly reduce material requirements could include integrating solar PV in building designs to reduce the material demands of support structures, and optimization of the locations of new wind and solar PV installations to reduce the need for network expansion. Assessments of these strategies would require an expansion of the existing system boundary in terms of materials, and/or technologies included in the analysis, as well as in terms of methodologic approaches. Support structures, for example, require more bulk materials than the concrete and steel studied in **Paper I**, especially for solar PV. An electricity network constitutes a new application, necessitating additional stock development. To this end, Chen et al. [43] have provided data on the metal requirements of electrical grid systems for wind and utility-scale solar PV at a global level. Optimizing the location, requires spatially explicit analyses. To this end, Liu et al. [95] have provided further insights into how spatial analysis can help enhance material stocks and flows analyses.

Strategies that indirectly reduce the material requirements for VRE production by reducing the electricity demand include strategies that could be applied in the electric mobility and buildings sectors. Research on this topic could pose the question: *What are the material implications in variable renewable electricity sources be from applying demand-side/ sufficiency measurers in transport/ building sector?* In the electric mobility sector, the strategies may include car sharing, downsizing vehicles, modal shift through the expansion of public transport systems, and reducing driving range. In the buildings sector, sufficiency measures such as reduced floorspace per capita could be investigated. To investigate these topics, it would be necessary to link an electricity systems model that addresses demand-side strategies to our MFA model.

2. Investigating the material equivalent of climate justice

Our research to date contributes to answering empirical questions regarding the specific material needs, and their development over time, for VRE technologies in decarbonization strategies. Steep increases in the demands for most of the materials used in the low-carbon transition, due to the growth of the electricity demand and a move towards renewable energy technologies, are expected. Even though we show that for 7 of the 11 metals studied CE strategies are able to reduce the demands to levels lower than the current ones, this change only occurs toward the end of the scenario period. At the same time, research shows that even maintaining the current levels of material use at a global level is unlikely to be sustainable, so the total volumes of materials within the economies of developed countries must be reduced [96], [97], [98]. Indeed, Kalt et al. [99] have showcased the highly unequal distribution of metal stocks per capita between high- and low-income countries in terms of the electricity infrastructures. The total electricity consumption level includes basic needs satisfaction, prosperous consumption, and luxury consumption [100], with the latter not aligning with remaining within a just and safe operating space or avoiding overshooting the planetary boundaries [101].

Therefore, there is a need to direct research efforts towards the ways in which a material equivalent of climate justice can be addressed. Some studies have followed an egalitarian approach (equal per capita) in creating a material equivalent of climate justice (i.e., material footprint per capita as equivalent to emissions per capita) [62], [102], [103]. In doing so, those studies used different approaches to estimating the material space, including current annual global production level, global resource use, global reserves, global resources on the material side, and annual or cumulative population statistics. Advantages and disadvantages are associated with each approach. Furthermore, other distributive justice-sharing principles used for climate, such as prioritarian-, grandfathering-, utilitarian-, and sufficiency-based allocations may be explored, including their trade-offs. In addition, recent studies have provided estimates of the material requirements for decent living standards [100], [104]. Whether or not it is possible to translate these into material requirements for VRE is be a topic for a future investigation. Furthermore, in connection to the first possible direction of the work described above, demand-side mitigation strategies that explicitly consider planetary boundaries associated with Earth's material resources could be explored.

Another approach to showcasing justice aspects with regards to the material demands entails the assessment of spatially distributed environmental consequences related to metal consumption in one country or region. For example, Nakajima et al. [105] have investigated the land-use change associated with nickel mining around the world, as well as the land-use change induced by the final nickel demand in Japan. Such approaches require the linking of two industrial ecology methods, MFA and an input-output analysis. Whether conducting such an analysis for a specific sector (such as, VRE) is possible with currently available datasets needs to be investigated.

3. From primary demand to primary extraction, i.e., across the supply chain

Among the metal cycle stages (production, fabrication and manufacturing, use, waste management, and recycling (see [106]), this introductory essay covers the use, waste management and recycling stages, along with the associated losses during these stages. This results in estimations of the primary metal demand and the secondary supply. Future work could expand to include the stages prior to the use stage (i.e., production and fabrication and manufacturing, including the associated losses), in order to estimate the primary extraction requirements associated with the metals used in wind and solar PV applications. Careful consideration will be needed depending on whether the metals included in such analyses are host, co-product or by-product metals when integrating their production and fabrication stages.

By-product metals may be selectively extracted and refined from different steps of the host metal's production stage. Several of the metals included in **Paper II** are produced mainly or entirely as the by-products of primary commodities and currently have particularly low production yields [106]. However, since not all metal refineries are currently equipped with by-product recovery technologies, the implementation of such technologies could lead to an increase in the production of by-product metals relative to the production level of the host metal [107], [108]. For example, In and Ga, which are included in our analysis, are metals for which production could be increased by optimizing their recovery in the refining stages, i.e., without any need to increase extraction of the host metal [108]. The values for these potential increases could be used in scenario analyses to estimate the primary extraction levels associated with VRE generation scenarios.

Appendix A: Recycling analysis

To investigate the potential impacts of recycling on the primary demand and secondary supply of metals, old scrap collection rates (herein referred to as *collection rates*) and recycling process efficiency rates are applied to the material outflows, and primary demand was calculated as follows:

$$SS_m(t) = outflow_m(t) \times collection_k(t) \times recycling_m(t)$$

$$PD_m(t) = inflow_m(t) - Secondary\ supply_m(t)$$

where $SS_m(t)$ is the secondary supply of metal m recovered through the recycling process, $collection_k(t)$ is the collection rate of solar PV or wind technologies at time t, and $recycling_m(t)$ is the recycling process efficiency rate per metal m at time t. $PD_m(t)$ is primary demand, which is a result of the gross demand (inflows) minus the $SS_m(t)$.

$SS_m(t)$ is further broken down into the secondary supply needed to be used within the system and the secondary supply that can be used for other applications, calculated as follows:

$$SS_{m,within\ the\ system}(t) = \begin{cases} PD_m(t), & PD_m(t) > 0 \\ 0\,, & PD_m(t) \leq 0 \end{cases}$$

$$SS_{m,for\ other\ applications}(t) = SS_m(t) - SS_{m,within\ the\ system}(t)$$

where $SS_{m,within\ the\ system}(t)$ is the quantity of secondary metal supply (recycled metals) at time t that can contribute to fulfil the gross metal demand within the wind and solar PV wind applications, and $SS_{m,for\ other\ applications}(t)$ is the remaining secondary supply at time *t* that can cover the metal demands in other applications.

Collection rates

The collection rate represents the rate at which a wind or solar PV technology that has reached its EoL arrives at a waste treatment facility. In the EU, solar PV modules are categorized as waste electrical and electronic equipment (WEEE) category VII. The European Directive on WEEE (2012/19/EU) sets forth a collection target of at least 65% of the average weight of electrical and electronic equipment (EEE) placed on the market over the preceding 3 years, from 2019 onward. This directive enforces the principle of Extended Producer Responsibility, mandating that the producer is responsible for the costs associated with the management of WEEE. The legislation also indicates an intention to update this collection target from 65% to 85% upon the availability of a European Commission methodology for estimating WEEE generation. Therefore, in our analysis, we apply a 65% collection rate for the Baseline scenario throughout the scenario period, while the Recycling scenario assumes a linear increase from 65% in 2021 to 85% in 2050.

For wind turbines, which are larger-scale installations than solar PV units, higher collection rates are assumed, in accordance with the paper of Lallana et al. [62]. In particular, we apply an 80% collection rate for the Baseline scenario throughout the scenario period, while the recycling scenario assumes a linear increase from 80% in 2021 to 95% in 2050.

Recycling process efficiency rate

The recycling process efficiency rate represents the rate at which the secondary raw materials contained in EoL technologies that have reached an official waste treatment facility are recovered. The process of recovering the same metal from different technologies may necessitate specific methods. Each technology's 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 metals associated with specific technologies is important. I gathered data for the recycling process efficiency rate, which measures the proportion of a material in the waste flows that is recycled for solar PV and wind technologies. Tables A1 and A2 provide the main assumptions made for the recycling process efficiency rates for the solar PV and wind technologies, respectively.

In the Baseline scenario, the current recycling process efficiency rate is applied and kept constant throughout the scenario period. For the Recycling scenario, recycling process efficiency rates are increased from their current values in 2021 to their maximum potential values in 2050. Two approaches were used for the data interpolation between 2021 and 2050. For all metals that currently have mature recycling markets (Cd and Te), the recycling process efficiency rate values were linearly interpolated, under the assumption that growth in recycling process efficiency rate will primarily be driven by optimization of the existing recycling processes. For all metals that are currently scarcely recycled from wind power and solar PV, on the other hand, the increase in annual recycling process efficiency rate is modeled using logistic functions to reflect the low recycling process efficiency rate until infrastructure is in place, during which the recycling process efficiency rate grows quickly, and over time the rate of growth decreases as the recycling market approaches saturation (Figure A1). Indeed, according to a previous study [19], for rapidly expanding markets such as solar PV and permanent magnets, Europe faces the challenge of initiating and scaling up new recycling processes and capacities. This is essential for managing effectively the technologies that are reaching their EoL. Consequently, the report anticipates that emerging recycling industries, particularly those focused on materials such as Si and REEs, are expected to experience rapid expansion post-2035 to 2040. This growth is expected to occur as the initial wave of clean energy technologies reaches the end of its lifecycle and needs to be replaced on a large scale, thus providing substantial volumes of waste for recycling.

Currently in Europe, there are initiatives in the initial phases that are aimed at recycling solar PV technologies. Notably, in Norway, Resitec is involved in the recycling of leftover wafers from the production of PV materials. Meanwhile, in France, Veolia has developed a recycling facility that is dedicated to the processing of solar panels that have reached the end of their lifespan, with the focus on the extraction and reuse of both Si and Ag [19]. However, techniques for the separation and purification of various metals must undergo large-scale testing, and economic challenges must be addressed to ensure that these processes are not only technically feasible but also financially viable. A key parameter for the economic viability of collection and recycling is the volume of EoL technologies [109]. Fishman and Graedel [68], for example, recommend that EoL permanent magnets should be stockpiled until sufficient recycling capacity is developed.

Table A1: Current and potential end-of-life recycling process efficiency rates per metal for the wind and solar PV technologies.

Metal	Current recycling process efficiency rate (%)	Source	Potential maximum recycling process efficiency rate (%)	Source
Ag	0 (<1)	[89]	94	[110], [111]
Cd	90	[89], [112]	95	[86], [111]
Te	90	[89], [112]	95	[86], [111]
Ge	0 (<1)	[113]	80	[113]
In	0 (<1)	[89], [106]	90	[111]
Ga	0 (<1)	[89], [106]	90	[111]
Se	0 (<1)	[89], [106]	90	[111]
Nd	0 (<1)	[89], [106]	90	See Table A2
Pr	0 (<1)	[89], [106]	90	
Dy	0 (<1)	[89], [106]	90	
Tb	0 (<1)	[106]	90	

Table A2: End-of-life recycling process efficiency rates per rare earth element for permanent magnets used in wind power, as recorded in the literature. (Rates in bold have not been included in the choice of rates used in our analysis because a definition of recycling process efficiency rate different to ours was used or a clear definition was not found).

Nd	Dy	Pr	Tb	Source
0.83	0.83	0.83	0.83	[13]
0.95	**0.95**	**0.95**	**0.95**	**[67]**
0.95	0.95	-	-	[89]
0.9	**0.9**	**0.9**	**0.9**	**[19]**
0.845 (70%–99%)	0.845 (70%–99%)	0.845 (70%–99%)	0.845 (70%–99%)	[114] considering different recycling methods
0.9	0.9	0.9	0.9	[69]
0.92	0.92	0.92	0.92	[115]

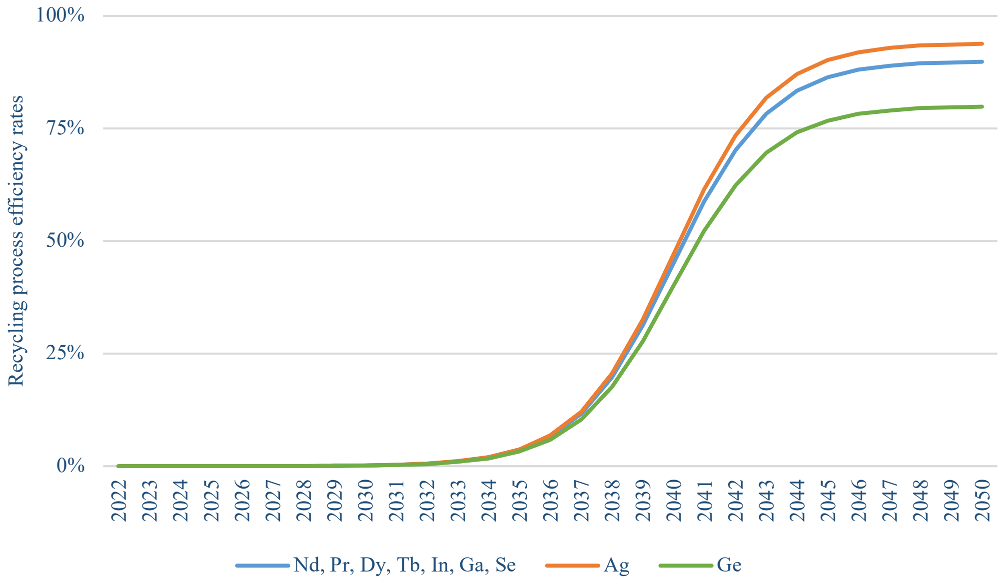

Figure A1: Logistic curves applied for maximum recycling process efficiency rates by 2050 for metals that currently have recycling process efficiency rates of zero.

Appendix B: Secondary supply availability

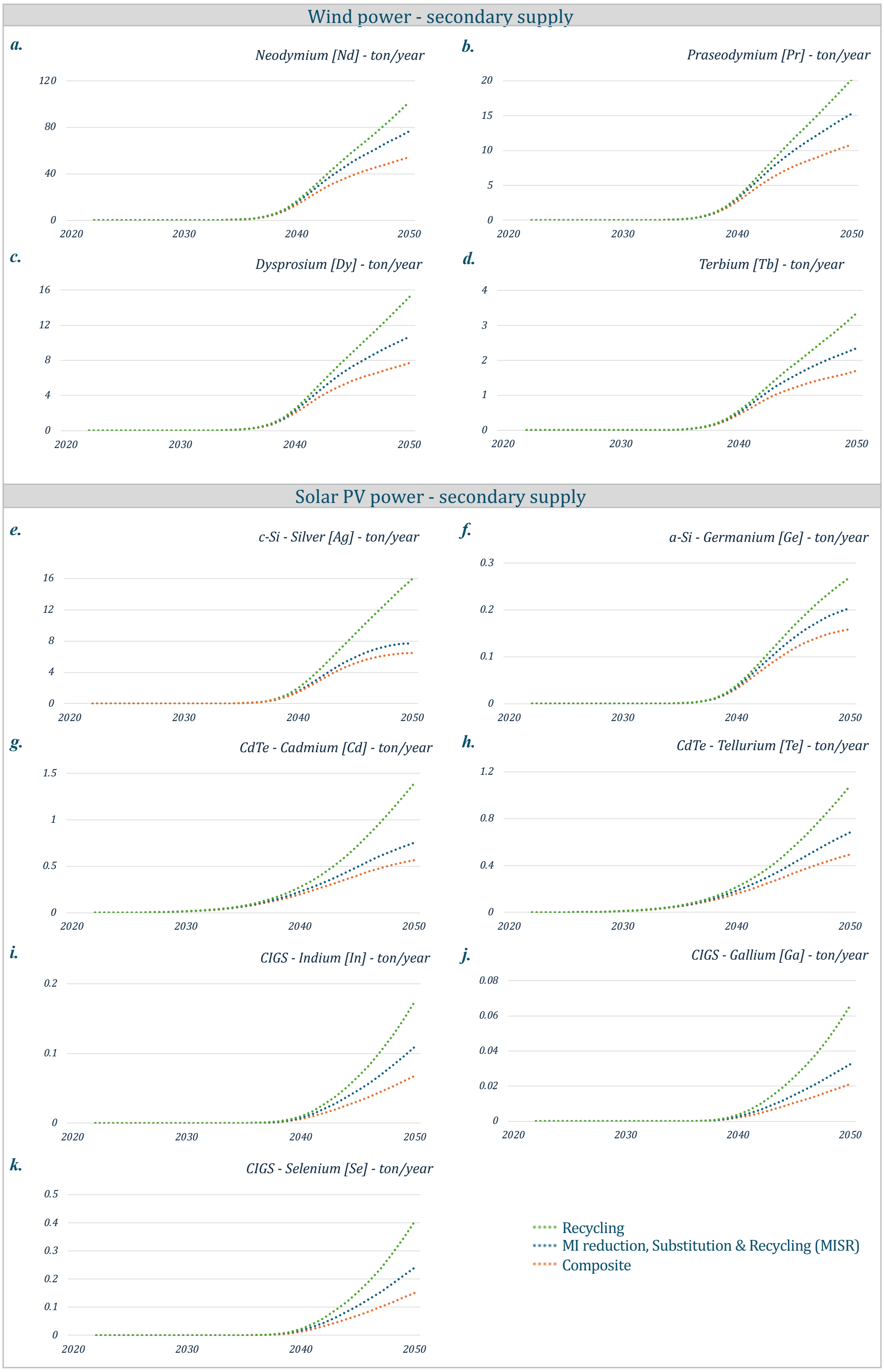

Figure B1: Secondary supply in tons per year for each metal used in wind power (**a-d**) and solar PV power (**e-k**) in Sweden in the Recycling scenario, the MI reduction, Substitution & Recycling scenario, and the Composite scenario. Source: **Paper II**, with additional analysis.

References

[1] K. Araújo, *Routledge Handbook of Energy Transitions*, 1st ed. London: Routledge, 2022. doi: 10.4324/9781003183020.

[2] T. E. Graedel, “Material Flow Analysis from Origin to Evolution,” *Environ. Sci. Technol.*, vol. 53, no. 21, pp. 12188–12196, Nov. 2019, doi: 10.1021/acs.est.9b03413.

[3] IPCC, “IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation,” United Kingdom and New York, NY, USA., O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds), 2011.

[4] L. T. Keyßer and M. Lenzen, “1.5 °C degrowth scenarios suggest the need for new mitigation pathways,” *Nat Commun*, vol. 12, no. 1, p. 2676, May 2021, doi: 10.1038/s41467-021-22884-9.

[5] A. Grubler *et al.*, “A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies,” *Nat Energy*, vol. 3, no. 6, pp. 515–527, Jun. 2018, doi: 10.1038/s41560-018-0172-6.

[6] J. Nijnens, P. Behrens, O. Kraan, B. Sprecher, and R. Kleijn, “Energy transition will require substantially less mining than the current fossil system,” *Joule*, vol. 7, no. 11, pp. 2408–2413, Nov. 2023, doi: 10.1016/j.joule.2023.10.005.

[7] W.-Q. Chen and T. E. Graedel, “In-use product stocks link manufactured capital to natural capital,” *Proc. Natl. Acad. Sci. U.S.A.*, vol. 112, no. 20, pp. 6265–6270, May 2015, doi: 10.1073/pnas.1406866112.

[8] M. D. Gerst and T. E. Graedel, “In-Use Stocks of Metals: Status and Implications,” *Environ. Sci. Technol.*, vol. 42, no. 19, pp. 7038–7045, Oct. 2008, doi: 10.1021/es800420p.

[9] S. G. Simoes and A. T. M. Lima, “Materials, resources, and CO2 impacts of building new renewable power plants to reach EU’s goals of carbon neutrality,” *Journal of Cleaner Production*, vol. 418, p. 138138, Sep. 2023, doi: 10.1016/j.jclepro.2023.138138.

[10] T. Watari, B. C. McLellan, D. Giurco, E. Dominish, E. Yamasue, and K. Nansai, “Total material requirement for the global energy transition to 2050: A focus on transport and electricity,” *Resources, Conservation and Recycling*, vol. 148, pp. 91–103, Sep. 2019, doi: 10.1016/j.resconrec.2019.05.015.

[11] S. Deetman, H. S. de Boer, M. Van Engelenburg, E. van der Voet, and D. P. van Vuuren, “Projected material requirements for the global electricity infrastructure – generation, transmission and storage,” *Resources, Conservation and Recycling*, vol. 164, p. 105200, Jan. 2021, doi: 10.1016/j.resconrec.2020.105200.

[12] G. Kalt, P. Thunshirn, F. Krausmann, and H. Haberl, “Material requirements of global electricity sector pathways to 2050 and associated greenhouse gas emissions,” *Journal of Cleaner Production*, vol. 358, p. 132014, Jul. 2022, doi: 10.1016/j.jclepro.2022.132014.

[13] T. Lee, Y. Yao, T. E. Graedel, and A. Miatto, “Critical material requirements and recycling opportunities for US wind and solar power generation,” *J of Industrial Ecology*, p. jiec.13479, Mar. 2024, doi: 10.1111/jiec.13479.

[14] D. Yu *et al.*, “Navigating the global mineral market: A study of resource wealth and the energy transition,” *Resources Policy*, vol. 82, p. 103500, May 2023, doi: 10.1016/j.resourpol.2023.103500.

[15] S. Wang *et al.*, “Future demand for electricity generation materials under different climate mitigation scenarios,” *Joule*, vol. 7, no. 2, pp. 309–332, Feb. 2023, doi: 10.1016/j.joule.2023.01.001.

[16] S. Davidsson and M. Höök, “Material requirements and availability for multi-terawatt deployment of photovoltaics,” *Energy Policy*, vol. 108, pp. 574–582, Sep. 2017, doi: 10.1016/j.enpol.2017.06.028.

[17] P. C. Sauer and S. Seuring, “Extending the reach of multi-tier sustainable supply chain management – Insights from mineral supply chains,” *International Journal of Production Economics*, vol. 217, pp. 31–43, Nov. 2019, doi: 10.1016/j.ijpe.2018.05.030.

[18] S. Giljum *et al.*, “A pantropical assessment of deforestation caused by industrial mining,” *Proc. Natl. Acad. Sci. U.S.A.*, vol. 119, no. 38, p. e2118273119, Sep. 2022, doi: 10.1073/pnas.2118273119.
[19] L. Gregoir and K. van Acker, “Metals for Clean Energy: Pathways to solving Europe’s raw materials challenge.” Eurometaux, Apr. 25, 2022. [Online]. Available: https://eurometaux.eu/media/rqocjybv/metals-for-clean-energy-final.pdf
[20] S. A. Miller, A. Horvath, and P. J. M. Monteiro, “Impacts of booming concrete production on water resources worldwide,” *Nat Sustain*, vol. 1, no. 1, pp. 69–76, Jan. 2018, doi: 10.1038/s41893-017-0009-5.
[21] A. Gasparatos, C. N. H. Doll, M. Esteban, A. Ahmed, and T. A. Olang, “Renewable energy and biodiversity: Implications for transitioning to a Green Economy,” *Renewable and Sustainable Energy Reviews*, vol. 70, pp. 161–184, Apr. 2017, doi: 10.1016/j.rser.2016.08.030.
[22] E. G. Hertwich, “Increased carbon footprint of materials production driven by rise in investments,” *Nat. Geosci.*, vol. 14, no. 3, pp. 151–155, Mar. 2021, doi: 10.1038/s41561-021-00690-8.
[23] H. Ritchie, M. Roser, and P. Rosado, “CO_2 and Greenhouse Gas Emissions.” [Online]. Available: https://ourworldindata.org/co2-and-greenhouse-gas-emissions [Online Resource]
[24] S. J. Davis *et al.*, “Net-zero emissions energy systems,” *Science*, vol. 360, no. 6396, p. eaas9793, Jun. 2018, doi: 10.1126/science.aas9793.
[25] J. Rissman *et al.*, “Technologies and policies to decarbonize global industry: Review and assessment of mitigation drivers through 2070,” *Applied Energy*, vol. 266, p. 114848, May 2020, doi: 10.1016/j.apenergy.2020.114848.
[26] G. De Leeuw, “The virtue of extraction and decolonial recollection in Gállok, Sápmi,” in *Coloniality and Decolonization in the Nordic Region*, 1st ed., London: Routledge, 2023, pp. 68–88. doi: 10.4324/9781003293323-5.
[27] J. R. Owen, D. Kemp, A. M. Lechner, J. Harris, R. Zhang, and É. Lèbre, “Energy transition minerals and their intersection with land-connected peoples,” *Nat Sustain*, vol. 6, no. 2, pp. 203–211, Dec. 2022, doi: 10.1038/s41893-022-00994-6.
[28] F. Creutzig *et al.*, “Demand-side strategies key for mitigating material impacts of energy transitions,” *Nat. Clim. Chang.*, vol. 14, no. 6, pp. 561–572, Jun. 2024, doi: 10.1038/s41558-024-02016-z.
[29] N. Bainton, D. Kemp, E. Lèbre, J. R. Owen, and G. Marston, “The energy-extractives nexus and the just transition,” *Sustainable Development*, vol. 29, no. 4, pp. 624–634, Jul. 2021, doi: 10.1002/sd.2163.
[30] B. K. Sovacool, “When subterranean slavery supports sustainability transitions? power, patriarchy, and child labor in artisanal Congolese cobalt mining,” *The Extractive Industries and Society*, vol. 8, no. 1, pp. 271–293, Mar. 2021, doi: 10.1016/j.exis.2020.11.018.
[31] UN, “Aligning Critical Raw Materials Development with sustainable development,” 2023. [Online]. Available: https://unece.org/sustainable-energy/publications/un-energy-policy-brief-aligning-critical-raw-materials-development
[32] United Nations Environment Programme, “Global Resources Outlook 2024: Bend the Trend – Pathways to a liveable planet as resource use spikes.,” International Resource Panel. Nairobi., 2024. [Online]. Available: https://wedocs.unep.org/20.500.11822/44901
[33] R. Ayres U., *Industrial metabolism; theory and policy*, vol. The Greening of Industrial Ecosystems. in in B. R. Allenby and D. J. Richards (eds), no. 23–37, vol. The Greening of Industrial Ecosystems. National Academy Press. Washington, DC.
[34] R. Carson, *Silent Spring*. Houghton Mifflin Company, New York, NY, 2002.
[35] B. Commoner, *The Closing Circle. Nature, Man and Technology.* Alfred A. Knopf, Inc., New York, NY., 1971.
[36] T. Zink and R. Geyer, “Circular Economy Rebound,” *J of Industrial Ecology*, vol. 21, no. 3, pp. 593–602, Jun. 2017, doi: 10.1111/jiec.12545.
[37] R. Geyer, B. Kuczenski, T. Zink, and A. Henderson, “Common Misconceptions about Recycling,” *J of Industrial Ecology*, vol. 20, no. 5, pp. 1010–1017, Oct. 2016, doi: 10.1111/jiec.12355.
[38] European Commission, “A new Circular Economy Action Plan For a cleaner and more competitive Europe.” 2020. [Online]. Available: https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en

[39] X. Zhong *et al.*, “Global greenhouse gas emissions from residential and commercial building materials and mitigation strategies to 2060,” *Nat Commun*, vol. 12, no. 1, p. 6126, Oct. 2021, doi: 10.1038/s41467-021-26212-z.

[40] S. Pauliuk *et al.*, “Global scenarios of resource and emission savings from material efficiency in residential buildings and cars,” *Nat Commun*, vol. 12, no. 1, p. 5097, Aug. 2021, doi: 10.1038/s41467-021-25300-4.

[41] N. M. P. Bocken, I. De Pauw, C. Bakker, and B. Van Der Grinten, “Product design and business model strategies for a circular economy,” *Journal of Industrial and Production Engineering*, vol. 33, no. 5, pp. 308–320, Jul. 2016, doi: 10.1080/21681015.2016.1172124.

[42] A. P. M. Velenturf, “A Framework and Baseline for the Integration of a Sustainable Circular Economy in Offshore Wind,” *Energies*, vol. 14, no. 17, p. 5540, Sep. 2021, doi: 10.3390/en14175540.

[43] Z. Chen, R. Kleijn, and H. X. Lin, “Metal Requirements for Building Electrical Grid Systems of Global Wind Power and Utility-Scale Solar Photovoltaic until 2050,” *Environ. Sci. Technol.*, vol. 57, no. 2, pp. 1080–1091, Jan. 2023, doi: 10.1021/acs.est.2c06496.

[44] A. de Koning, R. Kleijn, G. Huppes, B. Sprecher, G. van Engelen, and A. Tukker, “Metal supply constraints for a low-carbon economy?,” *Resources, Conservation and Recycling*, vol. 129, pp. 202–208, Feb. 2018, doi: 10.1016/j.resconrec.2017.10.040.

[45] X. Deng and J. Ge, “Global wind power development leads to high demand for neodymium praseodymium (NdPr): A scenario analysis based on market and technology development from 2019 to 2040,” *Journal of Cleaner Production*, vol. 277, p. 123299, Dec. 2020, doi: 10.1016/j.jclepro.2020.123299.

[46] A. Elshkaki and T. E. Graedel, “Dynamic analysis of the global metals flows and stocks in electricity generation technologies,” *Journal of Cleaner Production*, vol. 59, pp. 260–273, Nov. 2013, doi: 10.1016/j.jclepro.2013.07.003.

[47] A. Farina and A. Anctil, “Material consumption and environmental impact of wind turbines in the USA and globally,” *Resources, Conservation and Recycling*, vol. 176, p. 105938, Jan. 2022, doi: 10.1016/j.resconrec.2021.105938.

[48] L. Grandell, A. Lehtilä, M. Kivinen, T. Koljonen, S. Kihlman, and L. S. Lauri, “Role of critical metals in the future markets of clean energy technologies,” *Renewable Energy*, vol. 95, pp. 53–62, Sep. 2016, doi: 10.1016/j.renene.2016.03.102.

[49] V. Moreau, P. Dos Reis, and F. Vuille, “Enough Metals? Resource Constraints to Supply a Fully Renewable Energy System,” *Resources*, vol. 8, no. 1, p. 29, Jan. 2019, doi: 10.3390/resources8010029.

[50] S. Schlichenmaier and T. Naegler, “May material bottlenecks hamper the global energy transition towards the 1.5 °C target?,” *Energy Reports*, vol. 8, pp. 14875–14887, Nov. 2022, doi: 10.1016/j.egyr.2022.11.025.

[51] B. K. Sovacool *et al.*, “Sustainable minerals and metals for a low-carbon future,” *Science*, vol. 367, no. 6473, pp. 30–33, Jan. 2020, doi: 10.1126/science.aaz6003.

[52] K. Tokimatsu *et al.*, “Energy modeling approach to the global energy-mineral nexus: Exploring metal requirements and the well-below 2 °C target with 100 percent renewable energy,” *Applied Energy*, vol. 225, pp. 1158–1175, Sep. 2018, doi: 10.1016/j.apenergy.2018.05.047.

[53] K. Tokimatsu *et al.*, “Energy modeling approach to the global energy-mineral nexus: A first look at metal requirements and the 2 °C target,” *Applied Energy*, vol. 207, pp. 494–509, Dec. 2017, doi: 10.1016/j.apenergy.2017.05.151.

[54] T. Watari, K. Nansai, D. Giurco, K. Nakajima, B. McLellan, and C. Helbig, “Global Metal Use Targets in Line with Climate Goals,” *Environ. Sci. Technol.*, vol. 54, no. 19, pp. 12476–12483, Oct. 2020, doi: 10.1021/acs.est.0c02471.

[55] P. Berrill, A. Arvesen, Y. Scholz, H. C. Gils, and E. G. Hertwich, “Environmental impacts of high penetration renewable energy scenarios for Europe,” *Environ. Res. Lett.*, vol. 11, no. 1, p. 014012, Jan. 2016, doi: 10.1088/1748-9326/11/1/014012.

[56] S. Carrara, P. Alves Dias, B. Plazzotta, and C. Pavel, *Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system.* European Commission. Joint Research Centre.: Publications Office, 2020. Accessed: Feb. 09, 2023. [Online]. Available: https://data.europa.eu/doi/10.2760/160859

[57] L. Ciacci, I. Vassura, Z. Cao, G. Liu, and F. Passarini, "Recovering the 'new twin': Analysis of secondary neodymium sources and recycling potentials in Europe," *Resources, Conservation and Recycling*, vol. 142, pp. 143–152, Mar. 2019, doi: 10.1016/j.resconrec.2018.11.024.
[58] M. Lehtveer *et al.*, "Actuating the European Energy System Transition: Indicators for Translating Energy Systems Modelling Results into Policy-Making," *Front. Energy Res.*, vol. 9, p. 677208, Sep. 2021, doi: 10.3389/fenrg.2021.677208.
[59] G. Savvidou and F. Johnsson, "Material Requirements, Circularity Potential and Embodied Emissions Associated with Wind Energy," *Sustainable Production and Consumption*, vol. 40, pp. 471–487, Sep. 2023, doi: 10.1016/j.spc.2023.07.012.
[60] Z. Cao *et al.*, "Resourcing the Fairytale Country with Wind Power: A Dynamic Material Flow Analysis," *Environ. Sci. Technol.*, vol. 53, no. 19, pp. 11313–11322, Oct. 2019, doi: 10.1021/acs.est.9b03765.
[61] J. van Oorschot, B. Sprecher, B. Roelofs, J. van der Horst, and E. van der Voet, "Towards a low-carbon and circular economy: Scenarios for metal stocks and flows in the Dutch electricity system," *Resources, Conservation and Recycling*, vol. 178, p. 106105, Mar. 2022, doi: 10.1016/j.resconrec.2021.106105.
[62] M. Lallana, J. Torrubia, and A. Valero, "Metals for energy & digital transition in Spain: Demand, recycling and sufficiency alternatives," *Resources, Conservation and Recycling*, vol. 205, p. 107597, Jun. 2024, doi: 10.1016/j.resconrec.2024.107597.
[63] Adamas Intelligence, "Implications: Tesla Announces Next Generation Rare-Earth-Free PMSM," 2023. [Online]. Available: https://www.adamasintel.com/tesla-rare-earth-free-motor/
[64] E. Foehringer Merchant, "Super-efficient solar cells: 10 Breakthrough Technologies 2024," 2024. [Online]. Available: https://www.technologyreview.com/2024/01/08/1085124/super-efficient-solar-cells-breakthrough-technologies/
[65] Fraunhofer, "Out with the silver, in with the copper: A new boost for solar cell production," Sep. 2022. [Online]. Available: https://www.fraunhofer.de/en/press/research-news/2022/september-2022/out-with-the-silver-in-with-the-copper-a-new-boost-for-solar-cells.html
[66] D. Snieckus, "Offshore Wind Turbine 20MW Generator Ready 'Within Three Years''," 2019. [Online]. Available: https://www.rechargenews.com/wind/offshore-wind-turbine-20mw-generator-ready-within-three-years/2-1-711845
[67] P. Wang *et al.*, "Regional rare-earth element supply and demand balanced with circular economy strategies," *Nat. Geosci.*, vol. 17, no. 1, pp. 94–102, Jan. 2024, doi: 10.1038/s41561-023-01350-9.
[68] T. Fishman and T. E. Graedel, "Impact of the establishment of US offshore wind power on neodymium flows," *Nat Sustain*, vol. 2, no. 4, pp. 332–338, Mar. 2019, doi: 10.1038/s41893-019-0252-z.
[69] K. Habib and H. Wenzel, "Exploring rare earths supply constraints for the emerging clean energy technologies and the role of recycling," *Journal of Cleaner Production*, vol. 84, pp. 348–359, Dec. 2014, doi: 10.1016/j.jclepro.2014.04.035.
[70] A. Månberger and B. Stenqvist, "Global metal flows in the renewable energy transition: Exploring the effects of substitutes, technological mix and development," *Energy Policy*, vol. 119, pp. 226–241, Aug. 2018, doi: 10.1016/j.enpol.2018.04.056.
[71] A. Valero, A. Valero, G. Calvo, and A. Ortego, "Material bottlenecks in the future development of green technologies," *Renewable and Sustainable Energy Reviews*, vol. 93, pp. 178–200, Oct. 2018, doi: 10.1016/j.rser.2018.05.041.
[72] B. McLellan, E. Yamasue, T. Tezuka, G. Corder, A. Golev, and D. Giurco, "Critical Minerals and Energy–Impacts and Limitations of Moving to Unconventional Resources," *Resources*, vol. 5, no. 2, p. 19, May 2016, doi: 10.3390/resources5020019.
[73] N. T. Nassar, D. R. Wilburn, and T. G. Goonan, "Byproduct metal requirements for U.S. wind and solar photovoltaic electricity generation up to the year 2040 under various Clean Power Plan scenarios," *Applied Energy*, vol. 183, pp. 1209–1226, Dec. 2016, doi: 10.1016/j.apenergy.2016.08.062.
[74] W. Li and T. Adachi, "Evaluation of long-term silver supply shortage for c-Si PV under different technological scenarios," *Natural Resource Modeling*, vol. 32, no. 1, p. e12176, Feb. 2019, doi: 10.1111/nrm.12176.

[75] E. Gervais, S. Shammugam, L. Friedrich, and T. Schlegl, “Raw material needs for the large-scale deployment of photovoltaics – Effects of innovation-driven roadmaps on material constraints until 2050,” *Renewable and Sustainable Energy Reviews*, vol. 137, p. 110589, Mar. 2021, doi: 10.1016/j.rser.2020.110589.

[76] Y. Zhou *et al.*, “Dynamic criticality of by-products used in thin-film photovoltaic technologies by 2050,” *Journal of Cleaner Production*, vol. 263, p. 121599, Aug. 2020, doi: 10.1016/j.jclepro.2020.121599.

[77] A. Elshkaki and L. Shen, “Energy-material nexus: The impacts of national and international energy scenarios on critical metals use in China up to 2050 and their global implications,” *Energy*, vol. 180, pp. 903–917, Aug. 2019, doi: 10.1016/j.energy.2019.05.156.

[78] A. Valero, A. Valero, G. Calvo, A. Ortego, S. Ascaso, and J.-L. Palacios, “Global material requirements for the energy transition. An exergy flow analysis of decarbonisation pathways,” *Energy*, vol. 159, pp. 1175–1184, Sep. 2018, doi: 10.1016/j.energy.2018.06.149.

[79] P. H. Brunner and H. Rechberger, *Handbook of Material Flow Analysis*, 0 ed. CRC Press, 2016. doi: 10.1201/9781315313450.

[80] E. Müller, L. M. Hilty, R. Widmer, M. Schluep, and M. Faulstich, “Modeling Metal Stocks and Flows: A Review of Dynamic Material Flow Analysis Methods,” *Environ. Sci. Technol.*, vol. 48, no. 4, pp. 2102–2113, Feb. 2014, doi: 10.1021/es403506a.

[81] P. Baccini and H.-P. Bader, *Regionaler Stoffhaushalt: Erfassung, Bewertung und Steuerung; Spektrum Akademischer Verlag*. Heidelberg, Germany, 1996.

[82] Svenska Kraftnät, “Långsiktig marknadsanalys 2021. Scenarier för elsystemets utveckling fram till 2050,” Sundbyberg, Stockholm, Svk 2019/3305, 2021. Accessed: Oct. 02, 2023. [Online]. Available: https://www.svk.se/siteassets/om-oss/rapporter/2021/langsiktig-marknadsanalys-2021.pdf

[83] I. Karlsson, J. Rootzén, A. Toktarova, M. Odenberger, F. Johnsson, and L. Göransson, “Roadmap for Decarbonization of the Building and Construction Industry—A Supply Chain Analysis Including Primary Production of Steel and Cement,” *Energies*, vol. 13, no. 16, p. 4136, Aug. 2020, doi: 10.3390/en13164136.

[84] A. Månberger, “Critical Raw Material Supply Matters and the Potential of the Circular Economy to Contribute to Security,” *Intereconomics*, vol. 58, no. 2, pp. 74–78, Mar. 2023, doi: 10.2478/ie-2023-0016.

[85] V. Lundaev, A. A. Solomon, T. Le, A. Lohrmann, and C. Breyer, “Review of critical materials for the energy transition, an analysis of global resources and production databases and the state of material circularity,” *Minerals Engineering*, vol. 203, p. 108282, Nov. 2023, doi: 10.1016/j.mineng.2023.108282.

[86] T. Maani, I. Celik, M. J. Heben, R. J. Ellingson, and D. Apul, “Environmental impacts of recycling crystalline silicon (c-SI) and cadmium telluride (CDTE) solar panels,” *Science of The Total Environment*, vol. 735, p. 138827, Sep. 2020, doi: 10.1016/j.scitotenv.2020.138827.

[87] L. Silvestri, A. Forcina, C. Silvestri, and M. Traverso, “Circularity potential of rare earths for sustainable mobility: Recent developments, challenges and future prospects,” *Journal of Cleaner Production*, vol. 292, p. 126089, Apr. 2021, doi: 10.1016/j.jclepro.2021.126089.

[88] T. E. Graedel *et al.*, “What Do We Know About Metal Recycling Rates?,” *Journal of Industrial Ecology*, vol. 15, no. 3, pp. 355–366, Jun. 2011, doi: 10.1111/j.1530-9290.2011.00342.x.

[89] E. Dominish, S. Teske, and N. Florin, “Responsible minerals sourcing for renewable energy,” 2019.

[90] Y. Liang, R. Kleijn, A. Tukker, and E. Van Der Voet, “Material requirements for low-carbon energy technologies: A quantitative review,” *Renewable and Sustainable Energy Reviews*, vol. 161, p. 112334, Jun. 2022, doi: 10.1016/j.rser.2022.112334.

[91] European Commission, “Critical Raw Material Act,” 2024. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202401252

[92] UNEP, “An Assessment Report on Issues of Concern: Chemicals and Waste Issues Posing Risks to Human Health and the Environment,” United Nations Environment Program 978-92-807-3808–7, 2020. [Online]. Available: https://www.unep.org/resources/report/assessment-report-issues-concern-chemicals-and-waste-issues-posing-risks-human

[93] IEA, "Data and Statistics," International Energy Agency. Accessed: Jun. 15, 2020. [Online]. Available: https://www.iea.org/data-and-statistics
[94] H. Jin *et al.*, "Life Cycle Assessment of Neodymium-Iron-Boron Magnet-to-Magnet Recycling for Electric Vehicle Motors," *Environ. Sci. Technol.*, vol. 52, no. 6, pp. 3796–3802, Mar. 2018, doi: 10.1021/acs.est.7b05442.
[95] Y. Liu, W.-Q. Chen, T. Lin, and L. Gao, "How Spatial Analysis Can Help Enhance Material Stocks and Flows Analysis?," *Resources*, vol. 8, no. 1, p. 46, Mar. 2019, doi: 10.3390/resources8010046.
[96] T. Wiedmann, M. Lenzen, L. T. Keyßer, and J. K. Steinberger, "Scientists' warning on affluence," *Nat Commun*, vol. 11, no. 1, p. 3107, Jun. 2020, doi: 10.1038/s41467-020-16941-y.
[97] T. O. Wiedmann *et al.*, "The material footprint of nations," *Proc. Natl. Acad. Sci. U.S.A.*, vol. 112, no. 20, pp. 6271–6276, May 2015, doi: 10.1073/pnas.1220362110.
[98] T. Parrique *et al.*, "Decoupling Debunked: Evidence and Arguments against Green Growth As a Sole Strategy for Sustainability," European Environmental Bureau: Brussel, Belgium, 2019. [Online]. Available: https://eeb.org/library/decoupling-debunked/
[99] G. Kalt, P. Thunshirn, D. Wiedenhofer, F. Krausmann, W. Haas, and H. Haberl, "Material stocks in global electricity infrastructures – An empirical analysis of the power sector's stock-flow-service nexus," *Resources, Conservation and Recycling*, vol. 173, p. 105723, Oct. 2021, doi: 10.1016/j.resconrec.2021.105723.
[100] S. Pauliuk, "Decent living standards, prosperity, and excessive consumption in the Lorenz curve," *Ecological Economics*, vol. 220, p. 108161, Jun. 2024, doi: 10.1016/j.ecolecon.2024.108161.
[101] M. Heide, M. Z. Hauschild, and M. Ryberg, "Reflecting the importance of human needs fulfilment in absolute sustainability assessments: Development of a sharing principle," *J of Industrial Ecology*, vol. 27, no. 4, pp. 1151–1164, Aug. 2023, doi: 10.1111/jiec.13405.
[102] J. Hickel, D. W. O'Neill, A. L. Fanning, and H. Zoomkawala, "National responsibility for ecological breakdown: a fair-shares assessment of resource use, 1970–2017," *The Lancet Planetary Health*, vol. 6, no. 4, pp. e342–e349, Apr. 2022, doi: 10.1016/S2542-5196(22)00044-4.
[103] P. Viebahn, O. Soukup, S. Samadi, J. Teubler, K. Wiesen, and M. Ritthoff, "Assessing the need for critical minerals to shift the German energy system towards a high proportion of renewables," *Renewable and Sustainable Energy Reviews*, vol. 49, pp. 655–671, Sep. 2015, doi: 10.1016/j.rser.2015.04.070.
[104] H. Schlesier, M. Schäfer, and H. Desing, "Measuring the Doughnut: A good life for all is possible within planetary boundaries," *Journal of Cleaner Production*, p. 141447, Mar. 2024, doi: 10.1016/j.jclepro.2024.141447.
[105] K. Nakajima, K. Nansai, K. Matsubae, M. Tomita, W. Takayanagi, and T. Nagasaka, "Global land-use change hidden behind nickel consumption," *Science of The Total Environment*, vol. 586, pp. 730–737, May 2017, doi: 10.1016/j.scitotenv.2017.02.049.
[106] A. Charpentier Poncelet *et al.*, "Losses and lifetimes of metals in the economy," *Nat Sustain*, vol. 5, no. 8, pp. 717–726, May 2022, doi: 10.1038/s41893-022-00895-8.
[107] F. Fizaine, "Byproduct production of minor metals: Threat or opportunity for the development of clean technologies? The PV sector as an illustration," *Resources Policy*, vol. 38, no. 3, pp. 373–383, Sep. 2013, doi: 10.1016/j.resourpol.2013.05.002.
[108] M. Frenzel, C. Mikolajczak, M. A. Reuter, and J. Gutzmer, "Quantifying the relative availability of high-tech by-product metals – The cases of gallium, germanium and indium," *Resources Policy*, vol. 52, pp. 327–335, Jun. 2017, doi: 10.1016/j.resourpol.2017.04.008.
[109] V. V. Klimenko, S. V. Ratner, and A. G. Tereshin, "Constraints imposed by key-material resources on renewable energy development," *Renewable and Sustainable Energy Reviews*, vol. 144, p. 111011, Jul. 2021, doi: 10.1016/j.rser.2021.111011.
[110] G. A. Heath *et al.*, "Research and development priorities for silicon photovoltaic module recycling to support a circular economy," *Nat Energy*, vol. 5, no. 7, Art. no. 7, Jul. 2020, doi: 10.1038/s41560-020-0645-2.
[111] A. Domínguez and R. Geyer, "Photovoltaic waste assessment of major photovoltaic installations in the United States of America," *Renewable Energy*, vol. 133, pp. 1188–1200, Apr. 2019, doi: 10.1016/j.renene.2018.08.063.
[112] International Cadmium Association, "CdTe thin-film photovoltaics." [Online]. Available: https://www.cadmium.org/applications/photovoltaics/

[113] ESA, “Effective recycling for Germanium,” 2022. [Online]. Available: https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Shaping_the_Future/Effective_recycling_for_Germanium
[114] B. Roelofs, “Material recovery from dutch wind energy,” Leiden University, Delft University of technology, 2020. [Online]. Available: https://repository.tudelft.nl/islandora/object/uuid%3A164d7900-ef53-4347-be1d-7cd81ed5bc1d.
[115] R. Schulze and M. Buchert, “Estimates of global REE recycling potentials from NdFeB magnet material,” *Resources, Conservation and Recycling*, vol. 113, pp. 12–27, Oct. 2016, doi: 10.1016/j.resconrec.2016.05.004.

Reflections on inequities in academia

Hi, Fellow WISERs!

I have recently received emails encouraging me to read and submit to journals on renewable or clean energy that have abysmal gender representation on their Editorial Boards, showing around 80-90% men. I have written to them expressing my concern about this, noting that thousands of women are publishing in this space and that I would not support journals that don't do a better job with representation. I am but one person who (probably) has little to no impact. This got me to wondering if others might want to take collective action on this issue. I don't know what that looks like. I wanted to first see if this is an issue others would like to get involved in. If so, we could brainstorm approaches and then present these ideas to this and other relevant groups. Engaging men who also value greater gender diversity would be important, too.

Best,

Dr. ---
Assoc. Professor, ---

This is an email that recently landed in my mailbox from a WISER member. I felt sad, frustrated, and hopeful.

Writing a thesis is a time for introspection, a time to zoom out and try to see our research from a bird's-eye view. Writing a thesis can be a great opportunity to reflect on topics beyond our immediate research but still within our academic practices—practices we interact with, that may normalize unconsious biases, and may, unintentionally, reinforce them. Unfortunately, I believe these practices do not receive the attention they deserve.

There is no doubt that academia has generated inequities that manifest, among other, in a lack of diversity in editorial boards and citation practices[1-5]. Female scholars, members of the LGBTQ+ community, scholars from the Global South, Indigenous scholars, and other minorities are under-cited in academic papers and underrepresented on editorial boards.

Citations are intertwined with impact metrics, used as indicators of success, and reflect the fast-paced nature of academic production[6]. Citation practices, often made without consideration of their inherent power, can sustain inequalities within academia.

While I try to be aware of these inequities, I would be lying if I implied that I actively choose references that better reflect diversity in the field. Writing this section is more of a pledge to strive for better citation practices moving forward, for more learning, and for more action. As a first step, below I conduct an analysis of the female-to-male and Global South-to-Global North ratios of the editorial board members

---

1. Liu, F., Holme, P., Chiesa, M., AlShebli, B. & Rahwan, T. Gender inequality and self-publication are common among academic editors. *Nat. Hum. Behav.* **7**, 353–364 (2023).
2. Palser, E. R., Lazerwitz, M. & Fotopoulou, A. Gender and geographical disparity in editorial boards of journals in psychology and neuroscience. *Nat. Neurosci.* **25**, 272–279 (2022).
3. Teich, E. G. *et al.* Citation inequity and gendered citation practices in contemporary physics. *Nat. Phys.* **18**, 1161–1170 (2022).
4. Ross, M. B. *et al.* Women are credited less in science than men. *Nature* **608**, 135–145 (2022).
5. Son, J.-Y. & Bell, M. L. Scientific authorship by gender: trends before and during a global pandemic. *Humanit. Soc. Sci. Commun.* **9**, 348 (2022).
6. McCrory, G. *The Unseen in between Unpacking, Designing and Evaluating Sustainability-Oriented Labs in Real-World Contexts*. https://research.chalmers.se/en/publication/533275 (2022).

of the journals to which the papers appended to this thesis were submitted, as well as a female-to-male analysis of the citations in these papers. This only touches on two of the aspects that can shape experiences in science, which vary and are often overlapping along the lines of geography, sex, class, gender, race, ability, etc. And this is an individual action. Power lies in the collective.

For anyone interested in this, I find this piece[7] written by the editorial team of the journal *Climate Policy* a great call to action.

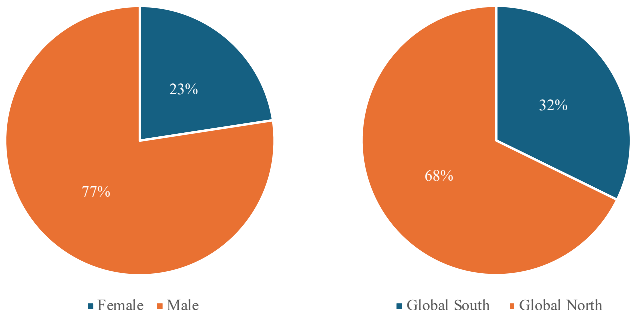

Figure 1: The female-to-male and Global North-to-Global South ratios of the members on the editorial board of the journal where **Paper I** of this thesis is published. The analysis presented in this figure was conducted with the support of artificial intelligence and my own analysis. Please note that while care was taken to ensure accuracy, there may still be errors in the data or interpretation.

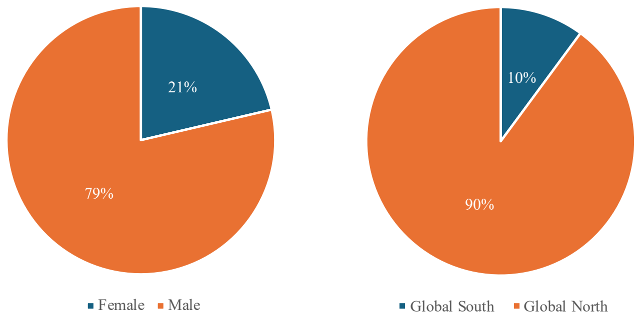

Figure 2: The female-to-male and Global North-to-Global South ratios of the members on the editorial board of the journal where **Paper II** of this thesis is submitted. The analysis presented in this figure was conducted with the support of artificial intelligence and my own analysis. Please note that while care was taken to ensure accuracy, there may still be errors in the data or interpretation.

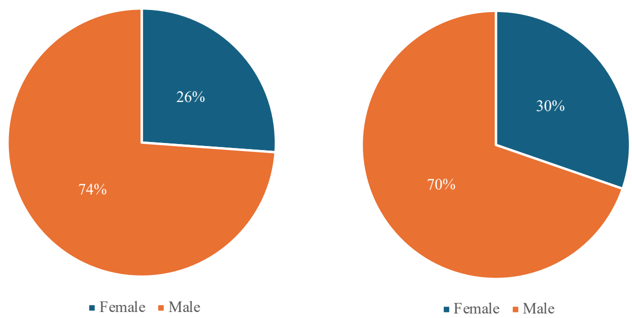

Figure 3: The female-to-male ratios of the first authors of the papers cited in Paper I (left-hand side) and Paper II (right-hand side) of this thesis. The analysis presented in this figure was conducted with the support of artificial intelligence and my own analysis. Please note that while care was taken to ensure accuracy, there may still be errors in the data or interpretation.

7. Schipper, E. L. F. *et al.* Equity in climate scholarship: a manifesto for action. *Clim. Dev.* **13**, 853–856 (2021).

Reflections on academic flying

By sustainable academia, we mean individual, collective, and institutional practices and behaviors that contribute to train researchers and produce scientific knowledge in a manner that is responsive to current and future generation needs, in a collective commitment to care for the 'Other', whether it be human or nonhuman.

Berkowitz and Delacour[8]

Academic flying is a sensitive topic for many in academia. After all, traveling is a significant part of many researchers' identities, and flying is often necessary for distant conferences and workshops. However, in the face of climate change, rethinking our approach to international collaborations and conference participation is crucial.

I first had to confront my air travel decisions when I realized that a trans-Atlantic flight I was planning to take for a training would exceed my annual carbon budget required to stay within the 1.5°C warming target. One round trip consumed my entire carbon budget for the year. Despite the large uncertainties in carbon budget estimations, it is hard to justify such a flight given its substantial carbon footprint. Later on, I had the opportunity to conduct research on air travel decisions in research organizations through a project that involved several interviews. This project resulted in the development of a tool for tracking, reflecting, and reducing air travel, as well as a policy brief to support more sustainable decision-making around air travel[9]. Through that experience, I discovered the many alternatives to air travel. Over time, while still far from perfect and continuously experimenting, I have learned to appreciate the value of traveling by ground, and I found role models who actively take on sustainable mobility in academia and beyond. I find the sustainable travel stories blog site of Lund University a great source of inspiration!

I recognize that pursuing a low-carbon PhD (or rather, a low-flight, or even a flight-less PhD, given that reducing flying is the most impactful climate action during a PhD) is complex and comes with contradictions. However, the lack of an easy solution should not deter us from striving to improve. The good news is that, contrary to common belief, research indicates that air travel has a limited impact on academic success[10].

I feel grateful that my project and supervisor at Chalmers allow for train travel, and I acknowledge the privileges that come with this and enable this. I hope Chalmers and universities around the globe continue to improve their travel policies, making train travel a more accessible option and making discussions on air travel more prominent in university circles. Below, I share some encounters and experiences from my alternative travel endeavors as part of my PhD thus far.

8. Berkowitz, H. & Delacour, H. Sustainable Academia: Open, Engaged, and Slow Science. *M@n@gement* 1–3 (2020) doi:10.37725/mgmt.v23.4474.
9. Savvidou, G., Lambe, F., Green, J. & Zavala, J. *Prepare for Landing: Practical Tips on Tracking, Reporting and Reducing Business Air Travel Emissions.* https://www.sei.org/publications/prepare-for-landing (2020).
10. Wynes, S., Donner, S. D., Tannason, S. & Nabors, N. Academic air travel has a limited influence on professional success. *J. Clean. Prod.* **226**, 959–967 (2019).

Photo 1: Amie and I at Hamburg train station, July 2024. I met Amie, a Swedish climate activist, on the night train between Basel and Hamburg on my way to Gothenburg after a PhD summer school in Barcelona. Amie has not taken any flights since 2017. She shared that she is well aware that choosing not to fly is not an option for everyone, and her decision to avoid flying frees up flights for people who cannot avoid it.

Photo 2: One of the many breaks during the bike road trip in Galicia as part of a summer school on green extractivism, June 2024. Traveling by bike for about 150 km enabled deep exchanges and learning. During the trip, we had the opportunity to meet with organizations and municipalities and have discussions on the topic of the summer school. We also did counter-mapping, which refers to the practice of creating maps that challenge mainstream representations of geography. This involved using our eyes, ears, and connecting to how a place made us feel, and mapping that from the perspective of the communities and social movements we visited to highlight issues such as land rights, environmental justice, and social inequalities that are often overlooked or misrepresented in conventional maps. To me, slow travel allows for a kind of thinking that we often miss in the hustle and fast pace of academia.

Photo 3: A stop in Copenhagen and a visit to the Danish Technical University during my train travel to the ISIE 11th International Conference on Industrial Ecology in Leiden, Netherlands, in June 2023 offered me a new perspective on the scale of the energy transition. I remember being awed by the size of the wind turbine blade and learning that turbines with even larger blades are already commercially available. One change I've made in my approach to work travel is to travel less frequently, but when I do, I aim to maximize opportunities for networking and learning. Train travel, inherently slower and more grounded, facilitates such thoughtful planning.