Electric vehicles, a silver bullet or merely a piece to the puzzle of an intergenerationally sustainable urban mobility sector?

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2021

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Dissertation submitted in partial fulfillment of a
Philosophiae Doctor degree in Environment and Natural Resources

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Bibliographic information:
Kevin Dillman, 2021, Electric vehicles, a silver bullet or merely a piece to the puzzle of an intergenerationally sustainable urban mobility sector? PhD dissertation, Faculty of Civil and Environmental Engineering, University of Iceland

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Printing:
Reykjavik, Iceland, September 2021

Abstract

Globally, electric vehicles (EVs) are being touted by countries and international organizations as a key transition technology to decarbonize the road transport sector. Yet, other researchers have suggested that EVs may not be a silver bullet solution, and public debates frequently question the embedded environmental impacts of EV's battery packs, electricity source, and potential to add to peak load, thus challenging grid systems and potentially requiring greater electrical generation capacity. EVs can be considered a technological solution to decarbonizing the urban transport sector, and studies have pointed out the need to consider both behavioural (demand-side) and technological approaches.

This thesis attempts to address these challenging questions regarding EV integration through a multi-layered approach in which EVs are assessed at a product and urban level in terms of greenhouse gas (GHG) emissions and electricity grid peak load impacts. Lastly, the thesis aims to characterize an intergenerationally 'safe and just' urban mobility system to contextualize the discussion surrounding EVs within a global sustainability framework, allowing for interpretation of what development pathways may provide the best results in terms of sustainability.

Intending to expand the conversation surrounding EVs, the results of the thesis suggest that a large-scale integration of EVs without car fleet reductions and other Avoid-Shift-Improve strategies may not be sufficient for achieving this intergenerational 'safe and just' sustainability. Rather than taking an EV-centric technological approach, it is suggested that accessibility and behavioural approaches should be equally considered, with the approach taken relevant to the context of the urban area in question when attempting to decarbonize a region's road transport sector. Thus, rather than seeing EVs as a silver bullet, this research suggests that they should seen as a single potential solution within a suite of solutions that should be used in the right context (i.e. low carbon electrical grid intensity and situations where the accessibility, travel distance, and public/active transport modes cannot provide sufficient mobility provisioning). It is the aim of this thesis that the results of this work can be used to inform policy makers and urban planners of the value of taking balanced supply- and demand-side solution approaches relevant to the local context and help them develop more sectorally-focused policies tied to sectorally characterized 'safe and just' state to help guide the urban mobility sector towards intergenerational sustainability.

Útdráttur

Á heimsvísu eru rafknúin farartæki (EVs) kynnt af löndum og alþjóðastofnunum sem lykiltæki í umbreytingunni til að minnka losun í vegaflutningum. Samt hafa vísindamenn gefið til kynna að rafbílar séu kannski ekki besta lausnin og opinber umræða efast oft um innbyggð umhverfisáhrif rafhlaðna, raforkugjafans og möguleika á að auka á hámarksálag og storka þannig rafmagnskerfinu sem geti krafið meiri raforkuframleiðslu. Líta má á rafbíla sem tæknilausn til að draga úr kolefnislosun í flutningageiranum í þéttbýli og rannsóknir hafa bent á nauðsyn þess að huga að hegðunaraðferðum (eftirspurnarhliðinni) og tæknilegum aðferðum.

Þessi ritgerð reynir að takast á við þessar krefjandi spurningar varðandi samþættingu rafbíla með marglaga nálgun þar sem rafbílar eru metnir á vöru- og þéttbýlisstigi með tilliti til losunar gróðurhúsalofttegunda (GHG) og áhrifa á hámarksálag raforkunetsins. Loks miðar ritgerðin að því að einkenna „öruggt og réttlátt“ hreyfanleikakerfi í þéttbýli milli kynslóða til að setja umræðuna um rafbíla í samhengi innan alþjóðlegs sjálfbærniramma, sem gerir kleift að túlka hvaða þróunarleiðir geta gefið bestan árangur hvað varðar sjálfbærni.

Niðurstöður ritgerðarinnar er ætlað að bæta við umræðuna um rafbíla og benda á að stórfelld aukning rafbíla án þess að minnka bílaflota og aðrar avoid-shift-improve aðferðir gæti ekki verið nægjanleg til að ná fram þessari „öruggu og réttlátu“ sjálfbærni milli kynslóða.

Í stað þess að nota rafbílamiðaða tækninálgun er lagt til að aðgengis- og hegðunaraðferðir verði jafnt skoðaðar í samhengi við viðkomandi þéttbýli þegar reynt er að minnka kolefnislosun vegasamgangna á því svæði.

Þess vegna, frekar en að líta á rafbíla sem silfurkúlu, benda þessar rannsóknir til að rafbílar séu aðeins ein möguleg lausn innan mengis fjölda lausna sem ætti að nota í réttu samhengi (þ.e. lágt kolefnisrafmagnsstyrkur og aðstæður þar sem aðgengi, fjarlægðir og aðrir flutningsmátar geti ekki veitt nægjanlegan hreyfanleika).

Markmið þessarar ritgerðar er að hægt sé að nota niðurstöður hennar til að upplýsa stefnumótendur og borgarskipulagsfræðinga um gildi þess að fara leið sem tekur mið af bæði framboðs- og eftirspurnarhliðinni sem tekur einnig tillit til staðbundins samhengis ásamt því að hjálpa þeim einstaklingum að þróa með sér nálgun sem byggi á sectorally-focused nálgun sem einkennist af „öruggri og réttlátri“ nálgun sem ætlað er að hjálpi við hreyfanleika í þéttbýli í átt að sjálfbærni milli kynslóða.

Dedication

This work is dedicated to my brilliant advisors who I could not have achieved this without, my friends who keep me sane and my life full of adventure, to my family, my brother and father who have always supported me, and most of all, to my mother, without whom none of this would have been possible.

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This thesis takes a multi-scale approach to explore the environmental benefits and of implications of EVs in the scope of global intergenerational sustainability. It is a compilation of the following four published peer-reviewed journal articles:

Paper I (P1)

Dillman, K. J., Árnadóttir, Á., Heinonen, J., Czepkiewicz, M., & Davíðsdóttir, B. (2020). Review and meta-analysis of EVs: Embodied emissions and environmental breakeven. *Sustainability*, 12(22), 9390.

> Corrections to *Paper I (P1)*
>
> **Dillman, K. J.,** Árnadóttir, Á., Heinonen, J., Czepkiewicz, M., & Davíðsdóttir, B. (2021). Correction: Dillman et al. Review and Meta-Analysis of EVs: Embodied Emissions and Environmental Breakeven. *Sustainability*, 13(9), 5195.

Paper II (P2)

Dillman, K.J., Czepkiewicz, M., Heinonen, J., Fazeli, R., Árnadóttir, Á., Davíðsdóttir, B., & Shafiei, E. (2021). Decarbonization scenarios for Reykjavik's passenger transport: The combined effects of behavioural changes and technological developments. *Sustainable Cities and Society,* 65, 102614.

Paper III (P3)

Dillman, K. J., Fazeli, R., Shafiei, E., Jónsson, J. Ö. G., Haraldsson, H. V., & Davíðsdóttir, B. (2021). Spatiotemporal analysis of the impact of electric vehicle integration on Reykjavik's electrical system at the city and distribution system level. *Utilities Policy*, 68, 101145.

Paper IV (P4)

Dillman, K.J., Czepkiewicz, M., Heinonen, J., & Davíðsdóttir, B. (2021). A Safe and Just Space for Urban Mobility - A Framework for Sector-Based Sustainable Consumption Corridor Development. *Global Sustainability*, 1-42.

Author contributions

P1: Review and meta-analysis of EVs: Embodied emissions and environmental breakeven

Conceptualization, **K.D.** J.H..; Data curation, K.D., Á.Á., and J.H.; Formal analysis, **K.D.** Methodology, **K.D.** and J.H.; Visualization, **K.D.**; Writing—original draft, **K.D.**.; Writing—review and editing, **K.D.**., M.C., B.D. and J.H.; Project administration, **K.D.**; Supervision, J.H.; Funding acquisition, B.D. and J.H.;

P2: Decarbonization scenarios for Reykjavik's passenger transport: The combined effects of behavioural changes and technological developments

Conceptualization, J.H.,M.C., **K.D.**, and R.F.; Data curation, **K.D.**, Á.Á., and M.C.; Methodology, **K.D.** and J.H.; formal analysis, **K.D.**; Writing—original draft preparation, **K.D.** and M.C.; Writing—review and editing, **K.D.**, M.C., J.H., R.F., and B.D.; Visualization, M.C. and J.H.; Supervision, M.C., R.F. and J.H.; Project administration, **K.D.**, M.C., and J.H.; Funding acquisition, B.D., M.C., R.F., and J.H.

P3: Spatiotemporal analysis of the impact of electric vehicle integration on Reykjavik's electrical system at the city and distribution system level

Conceptualization, R.F. and **K.D.**.; Data curation, **K.D.**, E.S., H.H. and R.F.; Formal analysis, **K.D.** Methodology, **K.D.** and R.F.; Visualization, **K.D.**, and J.Ö.H.; Writing—original draft, **K.D.**.; Writing—review and editing, **K.D.**, R.F., and B.D.; Project administration, **K.D.**; Supervision, R.F.; Funding acquisition, B.D.;

P4: A Safe and Just Space for Urban Mobility - A Framework for Sector-Based Sustainable Consumption Corridor Development

Conceptualization, **K.D.**; Data curation, K.D.; Conceptual development, **K.D.**, M.C., and J.H.; Methodology, **K.D.**, M.C., and J.H.; Visualization, **K.D.** and M.C.; Writing—original draft, **K.D.**, M.C.; Writing—review and editing, **K.D.**., M.C., B.D. and J.H.; Project administration, **K.D.** M.C., and J.H.; Supervision, J.H. and B.D.; Funding acquisition, B.D. and J.H.;

Abbreviations

(In order of appearance)

PB - Planetary boundary

GHG - Greenhouse gas

EC - Ecological ceiling

SF - Social foundation

SDG - Sustainable development goal

SCC - Sustainable Consumption Corridor

IPCC - International Panel on Climate Change

IEA - International Energy Agency

ASI - Avoid-Shift-Improve

EV – Electric vehicle

BEV – Battery electric vehicle

PHEV – Plug-in hybrid electric vehicle

SUMP – Sustainable Urban Mobility Plan

LCA – Life Cycle Assessment

ICEV – Internal combustion engine vehicles

SUM – Sustainable urban mobility

RQ – Research question

ISO – International Organization for Standardization

LCI – Life Cycle Inventory

SAS – Story-and-Simulation

TTW – Tank-to-Wheel

WTT – Well-to-Tank

LDMI – Log Mean Divisia Index

Acknowledgements

First and foremost, within my acknowledgements, I would like to thank and acknowledge my primary supervisor Jukka Heinonen. You one time mentioned to me that you are not sure I manage to get the many things I sign myself up for done, but it is actually I who am amazed. The time, effort, dedication, and thoughtful advising you provide to the many students you mentor, on top of teaching and being a father and husband is inspirational. I am glad to have you both as an advisor and as a mentor. I look forward to more darts and ping pong sessions.

Second, I would like to thank Brynhildur Davíðsdóttir. It was by your urging and support that I was able to become and Ph.D. student (and funding of course), and your advising since my time of a lowly incoming Master's student in a new country has helped guide my time in Iceland as well as constantly improving my work, particularly in understanding the broader applications of our work in the larger scheme of things.

Further, I would like to thank my additional two advisors, Michał Czepkiewicz and Reza Fazeli for your guidance during my studies. Particularly towards Michał, I felt our initial approaches towards our work could at times differ, but every time it was precisely these differences which led to some of the best and most interesting conclusions. Additionally, your knowledge of the literature has always interested and astounded me and has greatly enriched my time as a Ph.D. candidate.

I would additionally like to acknowledge some of my additional colleagues such as Bjarni Herrera, Hafþór Ægir Sigurjónsson, Snorri Egilsson, Hólmfríður Sigurðardóttir, Marta Rós Karlsdóttir, amongst many others for the consistent passion and sustainability work we have done together, as well as for the friendliness you have shown a foreigner in your country which has made my time in Iceland what it was.

Lastly, I would like to thank and acknowledge the Icelandic research council (RANNIS) who supported project [grant number 185497-051, 2019] as well as the Icelandic Road Authority (Vegagerðin) for their support of our transportation research.

1 Introduction

The Brundtland Report (1987) defined sustainable development as, "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987). While this was not necessarily the start of actions towards sustainability, the publication of this report was a landmark moment in which sustainable development, its definition, and its importance were globally agreed upon. Interestingly, this moment marks approximately a midpoint between the start of what some earth scientists have characterized as the beginning of the 'Great Acceleration' (starting in the 1950's) and current times (Steffen et al. 2004; Steffen et al. 2015). This 'Great Acceleration' and the concept's defining graphs describe the joint exponential growth of socio-economic (such as population, real GDP, urban population, energy use, transportation, and tourism) and Earth System trends (such as atmospheric carbon dioxide and methane levels, surface temperatures, ocean acidification, and tropical forest loss) (Steffen et al. 2004). These graphs have been used as evidence by earth scientists to describe our entrance into the Anthropocene, described as the exit of the Earth's current stable Holocene era and the entrance into a new geological epoch in which humans are the leading cause of global environmental variability (Crutzen, 2016; Crutzen and Stoermer, 2000; Steffen et al. 2007). There have been some debates regarding the formalization of the Anthropocene as well as its official onset (Finney, 2014; Gibbard and Walker, 2014); the range typically sits between 1750-1950[1]. These dates correspond with the first noted human-induced increase in CO_2 concentrations in Earth's atmosphere, aligning with both our first major use of fossil fuels with the steam engine and the beginning of the great acceleration of socio-economic and earth system trends.

While debates can be had regarding the formalization of an epoch, the importance of these socio-economic and earth system trends cannot be understated. Röckstrom et al. (2009) helped put these trends into context through the establishment of the Planetary Boundaries (PBs), which define a set of environmental thresholds that attempt to delineate the rough range of ecological state indicators[2] which, if crossed, could cause non-linear changes to the Earth System at a continental to global scale. These changes would, in turn, move humanity out of Earth's current 'safe' state, thus threatening humanity's societal development (Steffen et al. 2015). Of the seven PBs which have been quantified, two of them have been assessed to have already been transgressed, namely, biodiversity and biogeochemical flows, while two other boundaries are in the danger zone of being surpassed, namely, climate change and land system changes (Steffen et al. 2015; Raworth 2012).

[1] There have additionally been arguments made for an Early-Anthropocene approach, in which the first impacts of humans on the environment such as microbiotic change (Wilkonson et al. 2014) and habitat modification (Kaplan et al. 2011) can be seen as early as 8,000 years ago, though it has been argued that a changing stratigraphic epoch should be marked by systemic change to the Earth System, not just as the first markers of human existence (Zalaseiwicz et al. 2015).

[2] Stated as a "rough range" here due to the difficulty identified by Röckstrom et al. (2009) and Steffen et al. (2015) in defining exact ranges in which non-linear change could occur due to lack of scientific knowledge surrounding biophysical thresholds, complex systems and associated feedback loops and their potential interactions, and overshoot uncertainty.

These thresholds have been crossed while, simultaneously, vast international and intranational social inequities exist (Raworth 2012; Raworth 2017). The disparity between rich and poor and its relative impacts can be seen in the UN 2020 Gap Report (2020), which estimates that the top 1% and 10% income earner groups were responsible for 15% and 48% of global greenhouse gas (GHG) emissions, respectively. Oswald et al. (2020) further highlight these disparities, estimating that the top 10% income groups use 45% of all the energy allocated towards land transportation, whereas the bottom 50% of earners only use 10%. Beyond disparate environmental impacts and energy use, income inequality inter- and intra-nationally has been associated with social injustice and impacts in low-income communities, including increased violence, illness, and drug use (Wilkenson and Pickett 2012).

Using the 'safe' operating space defined by Röckstrom (2009), Raworth (2012; 2017) connected the PBs and human rights in an attempt to define a 'safe and just' operating space for humanity. First, Raworth utilized the PB framework to define the ecological ceilings (ECs). Second, she established a social foundation (SF) with 11 social objectives informed by the Rio+20 conference, the sustainable development goals (SDGs), and the main social goals aligned with forward-thinking policies at the time for formulation (O'Neill et al. 2018). Raworth defined the EC as the outer boundary that humanity should not surpass to remain 'safe' from dangerous Earth System changes and the SF as the inner boundary as the 'just' minimum that all human beings should have access to in order to live a good and dignified life. Circularly visualizing these ECs and SFs, as shown in Figure 1(a), the results were to the effect of a doughnut-shaped framework -- hence the name of her book Doughnut Economics, and framework by the same name -- in which the area inside of the doughnut depicts an intergenerationally 'safe and just' sustainable space for humanity. This interest in living in a 'safe and just space' that allows all to live a good life while not imposing on others' ability to do the same was additionally formalized in the Sustainable Consumption Corridor (SCC) framework (Di Guilio and Fuchs 2014; Fuchs et al. 2021). The SCC framework follows a similar approach to the doughnut economy framework, though it defines the EC-SF corridor using two straight lines, with the space between them representing the sustainable consumption space, as shown in Figure 1(b). The SCC framework focuses on consumption and its link to living a "good" life, where the satisfaction of needs required to live a "good" life is placed in the context of ECs (Fuch et al. 2021). The doughnut economy and SCC frameworks aim to integrate our need to live within the PBs while simultaneously supporting an intergenerationally just world that can meet the needs of all. Particularly within the SCC framework, the need to de-escalate consumption to stay within the PBs is often highlighted.

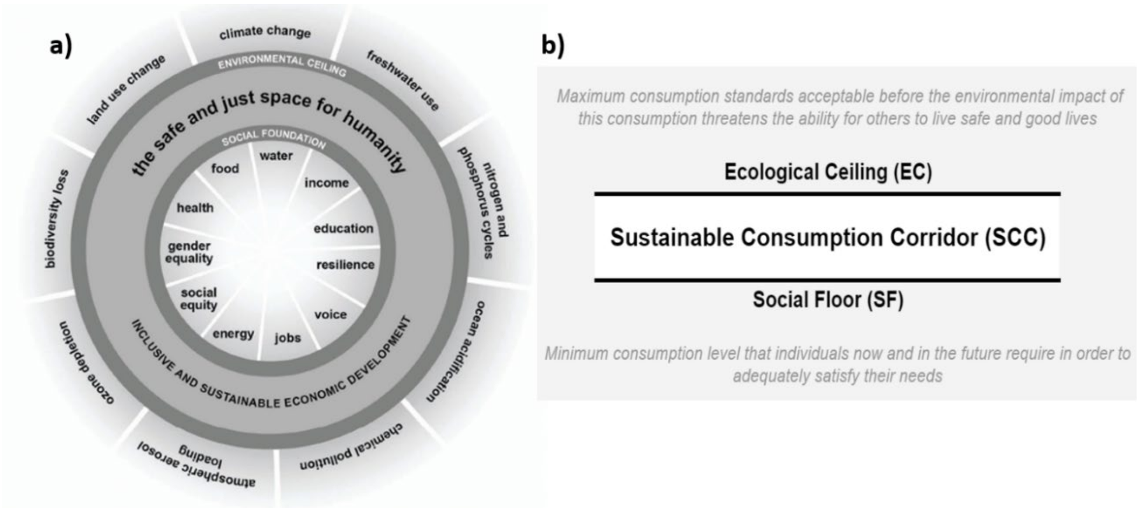

Figure 1. (a) Raworth's (2017) illustration of the 'safe and just' space for humanity with the Social Foundation and Environmental Ceiling depicted (image taken from Raworth 2017). (b) illustration of a Sustainable Consumption Corridor (image taken from Dillman et al. (2021c), adapted from Fuchs et al. 2021).

Within the discussion of PBs and their transgression, climate change has perhaps received the greatest amount of international focus. From the time of the Brundtland Report, the International Panel on Climate Change (IPCC) was established and has since published five Assessment Reports, the first in 1990, and is currently in the midst of the long process of preparing the 6th Assessment Report (AR6). The AR6 synthesis report will not be published until 2022, however, the results from the first working group already point towards a dire need for change to avoid catastrophe due to climate change. It states that unless deep GHG reductions occur in the next few decades, global warming of 1.5-2°C will be exceeded by 2100, if not much sooner (IPCC 2021). Since the IPCC began publishing its reports in 1990, total GHG emissions have gone from ~38 Gt CO_2eq emissions to ~58 Gt CO_2eq GHG emissions as of 2018 (Lamb et al. 2021), representing an approximately 53% growth over this period.

According to Lamb et al.'s estimations, in 2018, transportation emissions accounted for 14% of global emissions; Figure 2(a) shows how the transportation sector's emissions have grown over time, where the sector has seen roughly a 2% annual growth rate since 1990 (with some short-term variability). Disaggregating the emissions by region, Figure 2(b) demonstrates that Europe, North America, and East Asia are responsible for a large portion of road transport emissions (accounting for roughly 60%). Rapid growth can also be seen, however, in some of the other regions such as Southern Asia, South-East Asia, and Africa. This growth in developing regions emphasizes the global trend wherein as GDP per capita has risen in emerging economies, concurrent growth in urban sprawl and motorization has occurred, and mobility-related consumption has increased disproportionately with income (Wiedmann et al. 2020). These developments make reducing GHG emissions in the transportation sector a difficult task as demand continues to rise regardless of increasing pressure to address climate change, and 92% of the energy used to power vehicles still comes from fossil fuels (Lamb et al. 2021).

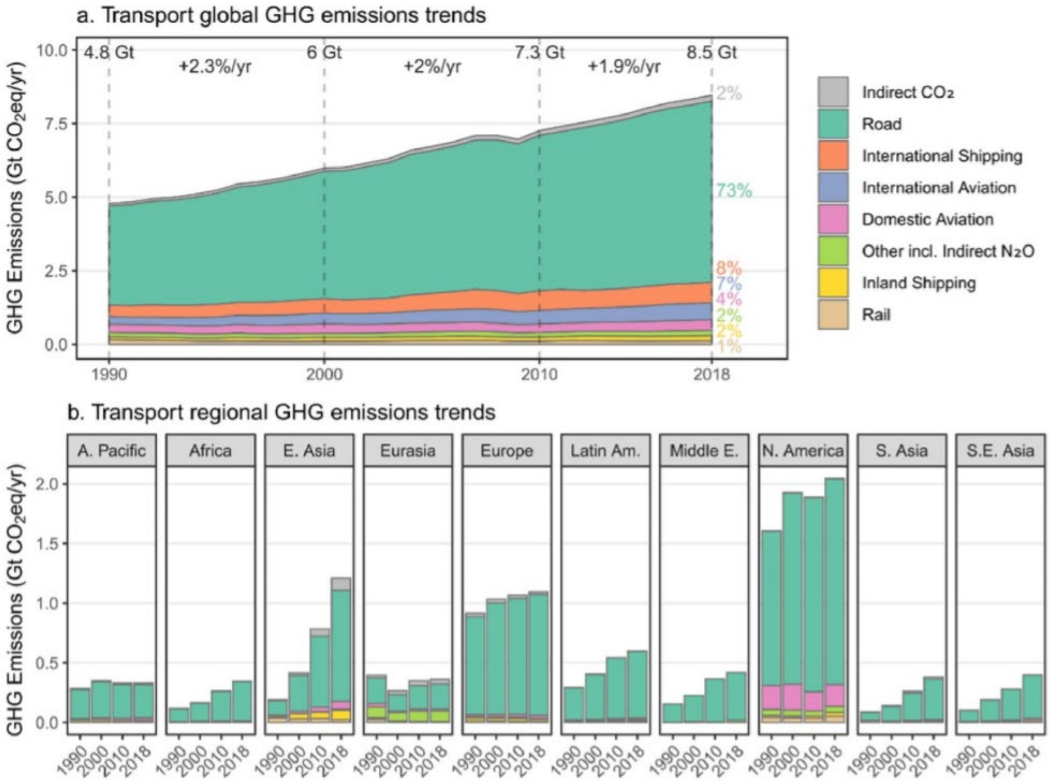

Figure 2. Global and regional GHG emissions trends for the transport sector. Panel (b) shows emissions at the years 1990, 2000, 2010, and 2018. International aviation and shipping is included in panel (a), but excluded from panel (b). (Image and adapted caption from Lamb et al. 2021)

The European emission profile provides an interesting example of this difficulty, wherein during the 1990-2018 time period, total GHG emissions from the EU decreased while ground transport emissions increased by roughly 20% during the same period (Lamb et al. 2021; EEA 2021). Additionally, similar to the inequalities at a global scale when it comes to disproportionate impacts by wealthy populations and externalities felt by less wealthy populations, at the European level, from 1990 to 2015, 27% of emissions were associated with the consumption of the top 10% wealthiest Europeans, which is equal to the emissions associated with the poorest 50% of Europeans (Gore and Alestig 2020). Sectorally, the transport sector sees social inequalities as well. For example Ivanova and Wood (2020) identified that across all European income percentiles ground transportation accounted for a sizable share of total per capita consumption emissions (often the largest category), but the lowest income quartile spent a disproportionate share of their income on transport, pointing towards fuel poverty issues, likely associated with a locked-in need for personal vehicles and high fuel costs (Middlemiss 2017). The benefits of transport systems additionally are often seen by the wealthier portions of society, while the less fortunate tend to have to disproportionately face the externalities associated with transport such as lack of accessibility to opportunities, freedom of movement, health externalities, and financial and community-related impacts (Lucas and Jones 2012).

Looking beyond the human and psychological toll caused by the Covid-19 pandemic, some academics have noted the opportunity presented by the pandemic and associated recovery plans to tackle some of the challenges associated with decarbonizing the road transport sector, and doing so in such a way that would promote a just transition (Markard and Rosenbloom 2020; Schwanen 2021). While not captured in Lamb et al.'s (2021) estimations, the impacts of Covid-19 and associated lockdowns showed that rapid reductions in mobility could occur with sufficient political will, despite the noted difficulty of decarbonizing the sector (Schwanen 2021). In fact, road transport was the sector which led to the greatest decrease in emissions globally during the first six months of the pandemic (Liu et al. 2020). Some studies have suggested that the pandemic and its implications could potentially provide the disruptive systemic shock required (Markard and Rosenbloom 2020) for the societal and political will to generate an accelerated non-linear socio-technical transition discussed in innovation literature (Geels 2002; Geels et al. 2017a). For the road transportation sector, socio-technical transition studies have considered the electrification of transport and integrated e-mobility as well as remote working as niche innovations that could lead to changes to the existing socio-technical systems which could represent movement towards a low-carbon transition (Geels et al. 2017b).

1.1 Focus on EVs

Such changes would be in line with the 2030 Agenda, approved by all member countries of the United Nations, particularly SDG 11: Sustainable Cities, target (11.2) to "provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons" (U.N. 2021). The International Energy Agency (IEA) (2020), has additionally discussed transforming ground transportation-related GHG emissions through the use Avoid-Shift-Improve (ASI) strategies for transport, as described by Creutzig et al. (2018), such as reduced travel demand, shifting transport modes, and reducing energy/emission intensity of transport modes. In terms of technical solutions, however, electric vehicles (EVs) are often touted as a leading solution, and the IEA has called for an even faster uptake of them to mitigate the emissions associated with combustion vehicles (IEA 2020). Thus far, of all the transport targets set by the IEA, EV growth rates represent one of the few that are currently being achieved. Battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) together have seen more than the annual 36% growth rate required to stay on track for the IEA's Sustainable Development Scenario (SDS), where the IEA estimates that 13% of the global car fleet will need to be electric by 2030 to achieve significant gains in transport decarbonization (IEA 2020). This global ambition to spur EV development has led to the establishment of the EV 30@30 initiative, where currently 14 countries have committed (with the number growing) to having 30% of new vehicle sales being EVs by 2030 (Clean Energy Ministerial 2019). This ambition can also be seen in the European Commission's Sustainable and Smart Mobility Strategy (2020), the first goal of which is to have 30 million zero-emission vehicles on European roads by 2030, which as of 2019 would represent ~6% of the vehicle fleet (ACEA 2021). While the importance of expanding more sustainable transport modes and making them more accessible is highlighted in the strategy, the electrification of ground transport fleets is a leading solution discussed in the plan.

Zooming in further to the Nordic region within Europe, this region has seen some of the highest integration rates of EVs, largely due to their implementation of some of the most aggressive pro-EV policies globally, with the primary objective being the decrease in the direct emissions from transport. For example, Norway has put forward the goal of having all light vehicle sales be zero-emission vehicles by 2025 (Norwegian Ministry of Transport and Communications 2016) and Iceland, Denmark, and Sweden have stated similar goals for 2030 (ICCT 2021). Further examples include policies such as reduced vehicle taxes for EVs, public support for charging infrastructure, and registration tax exemption, amongst other policies (IVL Sweden 2021), which aligns with the success in terms of integration rates seen so far in the Nordic region, with Norway, Iceland, Sweden, Denmark, and Finland globally in first, second, third, fifth, and sixth in terms of EV percentage of stock EVs, at 17%, 6.2, 3.6%, 2.4%, and 2.3%[3], respectively, as of 2020 (IEA 2021).

1.2 Urban perspectives

Zooming in further, with a majority of transportation occurring within cities, where it has been estimated that, globally, 60% of all kilometres travelled occurs within an urban context (Rode et al. 2014), the importance of taking an urban perspective when discussing transportation is particularly relevant. This holds especially true as urbanization rates continue to rapidly increase; as of 2007 more than 50% of the global population lives in urban areas, a figure which is predicted to reach 68% by 2050 (Ritchie and Roser 2018). With urban areas supporting an ever-increasing portion of the global population and, with it, a greater amount of mobility, how cities are structured to facilitate this transportation is an important aspect to consider when discussing mobility-related environmental and social impacts. Urban form and development are inherently related to the urban area's transportation infrastructure and vice-versa, and thus how a settlement takes its shape and the efficiency of its transportation system plays an important role in understanding the mobility patterns of the urban area (Rode et al. 2014). It has been shown that population density and transport energy use in urban areas are highly related, where more dense cities are significantly more likely to use less energy for transport per capita than less dense cities (Newman and Kenworthy 2015).

Given urban areas' important position as population centres and transportation system facilitators, cities and municipalities can play an important role as macro-level actors by setting policies and working to ensure that urban developments support sustainable development. For example, the Covenant of Mayors, an initiative of over 9,000 municipal authorities in over 57 countries, requires a commitment to reduce emissions from the partnering municipality by 40% by 2030 and to set climate action policies, with guidance provided for how to set effective climate action plans (EU Covenant of Mayors 2016). Another example is the C40, a network of nearly 100 of the largest cities with the goal of halving the emissions of these concentrated population centres by 2030 (C40 2021). These examples highlight the agency that cities can show on a global scale. Focusing further on urban mobility, urban centres have additionally been called to establish Sustainable Urban Mobility Plans (SUMPs) with the push to do so initiating in the EU, and multiple studies have reviewed these SUMPs in terms of best practices and comprehensiveness (May 2015; Cirianni et al. 2017; Kiba-Janiak and Witkowski 2019). In May's (2015) review, however,

[3] These numbers represent only BEVs

amongst other SUMP challenges, it was found that limited scenario generation skills and understanding were seen in modelling decarbonization development pathways and that this often led to an overemphasis of supply-side solutions. Recent efforts have been seen however by cities such as Amsterdam (2020) and Barcelona (2021) to adopt localized doughnut economy frameworks which would support a more intergenerational perspective to help shape urban policies that reflect Raworth's 'safe and just' sustainability thinking.

1.3 Knowledge gaps

With the importance of transportation emissions discussed and the global desire to transition towards EVs shown, it is then important to understand where knowledge gaps exist when considering EVs to be a sustainable solution. While nations and international initiatives have highlighted the imperative of transitioning to EVs, in the discourse surrounding EVs uncertain consumers and EV opponents exist. Central to their criticisms are the environmental impact of the battery packs required to produce EVs and the electricity source used to power the EVs (Olsson 2019; Ortar and Ryghaug 2019), thus creating lack of trust of the environmental benefits, which has been identified as a barrier to EV uptake (Biresselioglu et al. 2018). While there have been a plethora of EV Life Cycle Assessment (LCA) studies performed to assist in answering these concerns, large variabilities exist between studies, thus making cross-study comparisons a challenge (Marmoroli et al. 2018). Additionally, an overview of the methodological differences which have led to these studies has been understudied (Hawkins et al. 2012).

Considering the life cycle impacts of EVs at the urban level, the market which mass-market EVs hope to serve, the GHG mitigation potential of EVs has additionally been called into question, where multiple studies have questioned the ability of EVs to meet the carbon targets set by different cities/countries (Milovanoff et al. 2021; Shafiei et al. 2019; Hill et al. 2019). This is especially true when considering the direct and indirect impacts of transportation scenarios, which are often missing in the literature (Chester and Horvath 2009; Chester et al. 2013). Additionally, with calls to utilize ASI strategies for more sustainable development in transport, research gaps have been identified regarding the siloed approaches taken in studies, where too often studies either look at the mitigation potential of technological changes (such as EV integration) or behavioural changes (describing demand-side solutions such as decreased travel demand or a shift towards public and active transport modes), but rarely both (Brand et al. 2019; Creutzig et al. 2018; Anable et al. 2012). This further connects to the shortcomings identified in SUMPs, where supply-side solutions were often over-emphasized and skills in developing scenarios were found to be lacking (May 2015). Beyond GHG emissions, understanding the importance of pathway development at the urban level is relevant in terms of energy demand, where the IEA (2020) has estimated that a key shortcoming in the EV transition is the ability for electrical grids to support this increased demand. While studies have explored the potential grid-level impacts of EVs on the peak load, there is a lack of studies that look into the subsystems, which many consider to be more vulnerable to capacity issues than at the larger system level (Brady and O'Mahony 2016; Liu et al. 2011; Clement-Nyns et al. 2011; Short and Denholm 2006; Waddell et al. 2011).

Lastly, from a 'safe and just' global sustainability perspective, there are calls to develop sectoral approaches to SCC and doughnut economy frameworks in the research (Fuchs et al.

2021). Further, in O’Neill et al.’s (2018) paper, which attempts to assess the ability to achieve social thresholds whilst remaining within the PBs, they highlight the need to more effectively characterize social and physical provisioning systems - and mobility systems represent a key urban social provisioning system with significant physical infrastructure and impacts. This call supports concerns voiced in planetary boundary and sustainable indicator works in which the link between the two fields are almost always missing, representing a lack of ability to appropriately measure movement towards a ‘strong sustainability’ state and vice-versa where the state may be defined but are lacking relevant measurements of performance against the threshold (Fang et al. 2015; O’Neill et al. 2018; Holden et al. 2013).

1.4 Multi-scale Approach

The structure of the identified research gaps lent itself to a layered perspective, which this thesis used to formulate a multi-level approach to address them, as shown in Figure 3. At the first level, to address some of the most commonly cited product-level concerns surrounding EVs, this work identified the exploration of the life cycle GHG emissions associated with EVs as compared to internal combustion engine vehicles (ICEVs) and the potential reasons for the variability between individual EV LCA studies as a relevant first step. At the next level, with the identified need to assess the urban-level life cycle GHG emissions of EV integration whilst understanding the life cycle GHG implications between behavioural and technological developmental pathways, this thesis oriented its urban level research interests, as shown in Figure 3. These urban-level research interests additionally seek to understand the implications of different EV penetration rates on the electrical grid both at a system and subsystem level. Lastly, with the need for greater characterization of sectoral social provisioning systems, this work seeks to explore these issues through the lens of the urban passenger mobility sector. Through this lens, this thesis additionally oriented its research interests such that feedback could be provided on sustainable urban mobility (SUM) indicators to provide a greater perspective on how a sector-based SCC can be characterized to address the research gaps discussed.

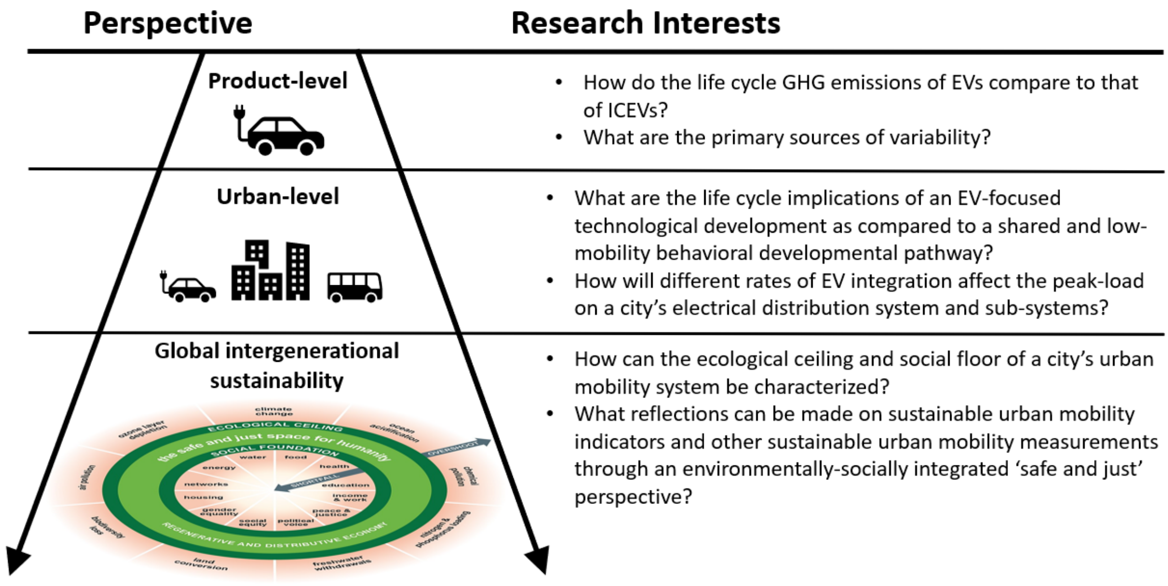

Figure 3. The multi-scale perspective taken within this research (with doughnut image taken from Raworth 2013)

1.5 Research questions

It is clear that, globally, society needs to reverse the trend of growing GHG emissions associated with the urban road transport sector if we hope to avoid transgressing the climate change PB. At a global, regional, and country level, EVs are considered a key technical solution to mitigate the GHG emissions associated with urban transport. Yet, comparative LCA studies which have been performed on EVs against ICEVs have shown varied results in terms of EVs' mitigation potential due to the production emissions associated with EVs (Hawkins et al. 2013) and the electricity source powering the EVs (Marmorli et al. 2018). Thus, addressing the research gaps and concerns regarding the LCA impacts of EVs -- both at a product and urban level -- seem particularly relevant. The need for this research is further heightened by the identified siloing of behavioural and technological approaches when assessing urban mobility system transformations and the overemphasis on supply-side solutions seen in the literature and SUMPs. Lastly, with calls to improve the characterization of social provisioning systems and sectoral approaches being suggested, this thesis thus seeks to address these knowledge gaps to develop a more nuanced approach to understanding the implications of EV integration. By understanding their direct and indirect emissions, potential grid impacts, relation to behavioural approaches, and urban developments, this thesis seeks to further discussions surrounding EVs and contextualize them in the frame of an intergenerationally sustainable urban mobility system subject to the regional context.

The goal of this approach is to develop an informed understanding of systemic life cycle impacts of EV integration to move the argument from whether EVs are capable of mitigating climate change impacts, to in what context this would occur, by how much, understanding what other pathways exist, and assessing whether this is aligned with inter and intra-generational sustainable development. Further, it can help understand if the promotion of EVs could potentially lead to a further socio-technical lock-ins of passenger vehicles and car dependence (Henderson 2020; Mattioli et al. 2020), potentially presenting another example of climate-focused policies and incentives leading to adverse social outcomes (Lamb et al. 2020) and/or need satisfier escalation (Brand-Correa et al. 2020).

Therefore, in an attempt to answer these questions and investigate the research gaps identified and their implications more deeply, this research took a multi-scale approach surrounding the topic of EVs, with the three research questions (RQs) of this thesis posed as:

> **RQ1:** *What is the direct and indirect decarbonization potential of EVs at the product level?*
>
> **RQ2:** *What is the direct and indirect decarbonization potential of EVs at the urban level (informed by a product-level life cycle perspective), and how will their integration potentially affect the electrical grid due to additional peak load?*
>
> **RQ3:** *How can an intergenerationally sustainable 'safe and just' urban mobility sector be characterized?*

These RQs can be seen as a coalescence of the multi-scale questions presented in Figure 3. As such, this thesis will also employ the multi-scale approach illustrated in the figure to answer them.

With the posing of these RQs, this thesis seeks to address the research gaps identified and provide value on multiple fronts. In answering RQ1, this thesis aims to provide insights for LCA researchers to provide more consistent and transparent methods to reduce uncertainty within EV LCA works. Additionally, through the quantitative results, the goal was to provide the context needed regarding the mitigation potential of EVs at different electrical grid intensities to provide data needed for more informed discussions surrounding the use of EVs in different grid contexts.

This information becomes further relevant for RQ2. At the urban level, the work in this thesis can be used by urban and electricity system planners to understand the implications of EV integration and different development pathways both in terms of GHG emissions as well as impacts on the peak load. This combined perspective provides context for two of the most relevant discussions surrounding EVs which are often assessed individually.

Lastly, by answering RQ3 and taking an intergenerational 'safe and just' sustainability perspective, this thesis hopes to aid policymakers and urban planners in characterizing what a 'strong sustainability' state could look like for the transportation sector. This type of research can assist urban planners, policymakers, urban transport researchers, and city-level sustainability initiatives (such as the Covenant of Mayors and C40) as urban populations continue to grow and the world continues to transgress the PBs whilst social needs are still not being met globally (Raworth 2017). For example, in O'Neill et al.'s (2018) country-level assessment of doughnut economy performance, they found that no country has successfully met all of their inhabitants' basic needs whilst staying within the PBs. In their concluding statements of this assessment, they remarked, "If all people are to lead a good life within planetary boundaries, then our results suggest that provisioning systems must be fundamentally restructured to enable basic needs to be met at a much lower level of resource use. [...] It is possible that the doughnut-shaped space envisaged by Raworth could be a vanishingly thin ring." This work thus places a focus on the urban transport sector as a provisioning system and attempts to understand how effectively EVs can mitigate the level of resource use and emissions within the perspective of moving the urban transport sector into Raworth's doughnut. With cities such as Amsterdam and Barcelona beginning to implement doughnut economy policies to understand their ability to exist in a 'safe and just space', to make these policies more operational, sectoral level approaches and frameworks will be needed. These can then be used to provide greater guidance to SUMPs and city climate action plans to align with global intergenerationally sustainable approaches.

By answering the three proposed research questions, this thesis aims to provide the information and frameworks needed to take a more granular sectoral approach to social provisioning whilst working to remain within Earth's carrying capacity by focusing specifically on the urban road transport sector and interpreting what the role a niche innovation, in this case EVs, has in helping to achieve intergenerational sustainability. This will hopefully allow for more integrated environmental and social perspectives, through which the resources and impacts associated with mobility-related social provisioning systems and their potential developmental pathways can be explored quantitatively and qualitatively. Additionally, by answering RQ3, through the provision of an integrated environmental and social characterization of a mobility-focused SCC this thesis aims to assist policymakers in avoiding the risk of implementing environmental policies which can cause negative social externalities, the potential of which has been shown to occur at times in Lamb et al.'s (2020) review of ex-post social implications of different environmental policies. This work will thus hopefully assist city-level policymakers and urban planners in thinking about how to restructure mobility systems through an informed system-level perspective aligned with intergenerational sustainability as opposed to a solution-focused perspective (such as an EV focus), such that the best suite of solutions is selected, whether that be through EV integration or other means.

With the value proposition defined, how to answer the RQs becomes the next relevant question. First, the following section will define the scope of the thesis, the data used, and the methodology of the thesis as a whole, along with the individual methods and research design of each constituting paper as relevant to the thesis. Next, the main results of the thesis are explained, and then similarly, the relevant by-paper results which provide the basis for the main results are described. The by-paper explanation of the research design and results are provided in the context of the thesis such that rather than summarizing each paper they provide the details of each paper relevant to the conclusions of the thesis. Lastly, the interpretation of the results can be found in the discussion section, ending with concluding remarks.

2 Scope, data, and methods

To describe the multi-scale approach taken in this thesis, first the scope, data, overarching methodologies, and research design followed by each study will be described. These sections will describe methods used across the thesis at an overarching level as well as a paper level, where relevant to the thesis.

2.1 Scope

Figure 3 illustrates the multi-scale approach taken to answer the research questions posed in this thesis. Table 1 describes the research carried out at each level, where the papers presented in Table 1 reflect the simplified structure shown in Figure 3 and describes their methods and relevance to the associated RQ.

This multi-scale approach was taken to develop a layered spatial and systemic understanding surrounding EVs. Thus, it is worth clarifying the specific scope of the study here, where the focus of this work was on the direct and indirect emissions and grid impacts from the urban passenger ground transport sub-sector. The focus on this sub-sector was chosen to understand more granularly the role of EVs in satisfying urban passenger transport demand and the greater urban passenger ground transport provisioning system. Thus, while the environmental importance and impact of freight, shipping, air transport, etc. are acknowledged (Savy and June 2013, Czepkiewicz et al. 2019), it was considered outside of the scope of the study, because the needs which are being served by these sub-sectors are different from the market which mass-market EVs are intended to serve. Both the direct and indirect life cycle GHG impacts associated with EVs and the urban passenger transport sub-sector were included in the scope due to their identified importance and identified often lacking perspective in the literature. However, it is worth noting that this was limited to the vehicles themselves, as the inclusion of environmental impacts from infrastructural changes is notably difficult, albeit important (Chester and Horvath 2009).

With the importance of taking a life cycle perspective on the different transportation options noted, at the product level, Paper I reviewed LCA studies to a) develop a greater understanding of EV LCAs and their contexts and reasons for variability, and b) to qualitatively assess the product level life cycle GHG benefit of EVs as compared against ICEVs using meta-analysis to provide a product level understanding of EVs. With the greater understanding of the direct and indirect GHG implication of EV use provided by Paper I, at the next level, Paper II and III then attempted to understand the urban-level implications of EV integration, using Reykjavik, Iceland's capital city, as a case study. Paper II continued the assessment of GHG emissions, however, it took a more critical look at contrasting technological and behavioural development pathways which are often assessed in isolation (Creutzig et al. 2018), in which EV integration represents the technological approach and movement towards other transport modes and reduced transport demand represent the behavioural approach. Building off the knowledge gained through Paper I, Paper II considered both the direct and indirect GHG implications of these two pathways. Paper III then considered the implications of EV integration in terms of potential peak load and associated impacts to the local transmission and distribution system at a city level. At the final level, Paper IV then took a global perspective in an attempt to understand the role that urban mobility has to play in intergenerational sustainability. To do so, the Planetary Boundaries were used to develop the Ecological Ceilings, and needs-satisfaction theory was used to develop mobility-focused Social Foundations.

Table 1. Connections between each paper and relevant research questions posed within the thesis and the associated implications of each paper

Scope of assessment	**Product level**[4]	**Urban level**		**Global level**
Paper	Paper I	Paper II	Paper III	Paper IV
Data	Metadata from LCA literature review	Metadata from Paper I, UniSysD_IS model, transportation survey	UniSysD_IS model, transportation survey	Literature-based
Methods	This paper performed an LCA review and a meta-analysis of the LCA results from the papers across the review. Environmental breakeven points and their calculations are additionally discussed in the paper.	The Story- and-Simulation approach was taken for the normative/backcasted scenario development in this paper in which behavioural, technological, and mixed pathways were assessed using Reykjavik as a case study.	An activity-based approach was used in this paper to develop a travel and charging behaviour model disaggregated by substation service areas to assess peak load impacts at an electrical grid and sub-system level using Reykjavik as a case study.	This paper proposes an initial framework for the development of sectoral SCCs, thus the methodology was established in this framework to create an example for a first characterization of an SCC for an urban mobility sector.
Relevance to RQ	**RQ1** Through the LCA review, greater context can be given to comparative EV LCA results, and the meta-analysis thus provided quantitative results of potential EV environmental benefits according to relevant contexts.	**RQ2** Through the quantitative modelling of the technological and behavioural development pathways the direct and indirect emission benefits and drawbacks of the two approaches could be considered.	**RQ2** Through the activity-based modelling taken, this paper was able to elucidate the potential impacts that increased EV integration could have on the electrical grid, which is an additional impact of import when considering supporting the development of EVs	**RQ3** With a lack of precedence for a defined intergenerationally sustainable 'safe and just' mobility system, this paper aimed to take a first step towards answering RQ3 through framework development following similar approaches found in ecological economic research.

[4] It is worth noting that Paper I analyze the performance of the product, in this case the vehicle itself, within the context of different grid intensities, both at the national level and across grid intensities. The product level remains as the scale of interest however, as the logic of this approach is to understand under which contexts the emission profile of a product itself changes.

The scope of the thesis varied geographically. Iceland and its capital city, Reykjavik, saw a significant focus. The city provides an interesting case study for this thesis with its focus on EVs, where it has a highly decarbonized electrical grid, some of the highest levels of car ownership in Europe, and Iceland has the second-highest penetration rate of EVs (23%) globally behind Norway (56%)[5] (IEA 2020). While Reykjavik may not provide a representative case study for many current global cities in terms of GHG intensity of the local electricity grid[6], it does, however provide an interesting future reference point in terms of how many cities are aiming to develop, with aims to decarbonize their associated electricity grids as well as electrify their car fleets. Thus, Reykjavik can illustrate a best-case, future state example for other cities.

Paper I took a broader European perspective, where environmental breakeven points were mapped across Europe, though the discussion did place a focus on end-case countries in terms of electrical grid intensity and associated country policies when it comes to EVs, with Iceland providing a good example of a country with a low emission intensity electrical grid and supportive EV policies. Paper II and III assessed city level aspects of EV integration and development pathways, using Reykjavik as a case study. Paper IV had no geographical scope, but did discuss the spatial complexity for defining a sector-focused SCC.

2.2 Data

The data used within each study varied. Paper I reviewed 19 EV LCA studies to develop a dataset providing qualitative characteristics of each study as well the life cycle emissions by phase for 71 different vehicle-grid condition combinations (including ICEV comparators). Papers II and III utilized a Gallup travel activity survey which had a total of 6,059 respondents who logged 23,666 travel activities, with the origin, destination, and transport mode data (Gallup 2017). The Gallup (2017) survey data was weighted in such a way that it reflected the actual Reykjavik population in terms of gender, age, and place of residence to ensure representativeness. Both papers additionally made use of the results from the UniSysD_IS model for electrification rate parameters in different scenarios (Shafiei et al. 2015; Shafiei et al. 2019). Paper II made further use of the data set developed in Paper I as well as other published data such as LCA of differing vehicle types, benchmarking to other literature and cities, as well as online datasets provided by Statistics Iceland (the National Statistical Institute of Iceland). Paper IV sought to establish a framework for sectoral SCC development and thus did not use any data sets. When attempting to apply indicators to the environmental and social thresholds developed in the study however, a SUM indicator set developed by Sdoukopoulos et al.'s (2019) review was used in which the study collected 2,264 indicators from 78 SUM indicator studies and provided the 47 most commonly used SUM theme/indicator sets in the literature. These SUM indicators were then applied to the mobility sector-focused SCC developed in Paper IV and assessed for their relevance to ECs and SFs, providing a platform for discussion for the future development of SUM indicators and sustainability indicators in general.

[5] This number includes both BEVs and PHEVs

[6] Where the carbon intensity of Iceland's electricity grid which supplies Reykjavik's electricity, is approximately 20 $gCO_2eq./kWh$, as compared to the E.U. average, which was estimated to be around 450 $gCO_2eq./kWh$ (with these numbers supplied from the data within Paper I)

Due to the importance of the transportation sector in global, regional, and national GHG emission inventories and humanity's continued transgression of the climate change PB, GHG emissions were this thesis' primary unit of assessment when considering the environmental impacts of EV integration. This thesis, however, also assessed the potential additional peak load added by EV integration and, through the SCC development in Paper IV, additional environmental impacts and social issues were considered in the EC and SF development.

2.3 Methods

This section describes the methodologies utilized for the multi-scale approach taken within this thesis. With this approach in mind, it was determined that the most logical procedure was to first provide a brief overview here of how the compilation of the methods served to answer the overarching RQs. Next, the methods and research design relevant to the thesis were described on a paper-by-paper basis in the following subsections, where the individual papers attempt to address the RQs of the thesis for each level in the manner described in Table 1. The results of these methods combined thus derived the overarching results for the multi-scale approach taken in this work..

Therefore, from a broad perspective, with an interest in understanding both the direct and indirect GHG emissions associated with EV use both at the product level and at the urban level, a holistic, multi-scale perspective is prevalent throughout the thesis. Paper I performed an LCA review and meta-analysis to compare EVs to diesel and petrol vehicles at a single product level. Paper II then used these results as a portion of the data used to model the direct and indirect GHG emissions from varying transport modes and vehicle types. This approach was taken to provide a more holistic perspective of GHG emissions compared to many urban-level assessments which frequently only consider the direct emissions associated with transport thus providing an incomplete picture of the global GHG emissions associated with the urban mobility systems (Chester and Horvath 2009; Chester et al. 2013). Further, to provide an urban-level perspective, this thesis additionally made use of two scenario analyses to allow for a temporal urban-level viewpoint as well. Paper II used the Story-and-Simulation (SAS) approach for scenario development, described in greater detail in Call-out Box 2. Paper III utilized different EV tax scenarios from Shafiei et al.'s (2019) to assess the impact of different levels of EV integration. These scenario approaches both performed temporal assessments from 2020-2050 to assess the long-term impacts associated with different levels of EV penetration rates. Lastly, the SCC framework was used to develop our indicator framework, which was used to take the first step in operationalizing a sector-focused SCC, in this case framing the SCC for the urban mobility sector. Using this SCC perspective, the results from Paper II were converted to a per capita basis to give a better understanding of different development pathways towards global, intergenerational sustainability in the transport sector.

2.3.1 Paper I: Methods and research design

Dillman, K. J., Árnadóttir, Á., Heinonen, J., Czepkiewicz, M., & Davíðsdóttir, B. (2020). Review and meta-analysis of EVs: Embodied emissions and environmental breakeven. *Sustainability*, 12(22), 9390.

Corrections to *Paper I (P1)*

Dillman, K. J., Árnadóttir, Á., Heinonen, J., Czepkiewicz, M., & Davíðsdóttir, B. (2021). Correction: Dillman et al. Review and Meta-Analysis of EVs: Embodied Emissions and Environmental Breakeven. *Sustainability*, 13(9), 5195.

Received: 23 September 2020 / Revised: 30 October 2020 / Accepted: 10 November 2020 / Published: 11 November 2020

Given the multi-scale approach of this thesis, the first step was to understand the product level environmental impacts of EVs to answer the question of if EVs could provide a suitable substitution to combustion vehicles. While EVs are commonly touted as a sustainable technological solution, previous studies have identified consumer concerns surrounding environmental impacts and resource use associated with the manufacturing of batteries and the source of the electricity powering EVs (where, when hoping to implement a sustainable solution the goal is not to simply displace fossil fuel use from the vehicles themselves to the use of fossil fuels in the electricity grid) (Egbue and Long 2012; Kumar and Alok 2020). To answer these questions, it is important to assess the entire life cycle of the compared vehicle types to understand where in the value chain and to what extent environmental impacts are occurring. Life Cycle Assessment is the primary assessment method used to perform this type of analysis. Call-out Box 1 describes the LCA method in greater detail.

Call-out box #1: Life Cycle Assessment

The concept of Life Cycle Assessment developed at its core in the interest of trying to understand if Product A or Product B leads to greater environmental impacts throughout the product's entire value chain. The concept took its form throughout the 1970s and 1980s as a method to perform the "compilation and evaluation of the inputs and outputs and the potential environmental impacts of a product system throughout its life cycle" (Guinee et al. 2011). First standardized in 1997 by the International Organization for Standardization (ISO) with updates made to this formalized framework since (Finkbeiner et al. 2006), LCA has become a globally accepted tool for environmental assessment[7]. Figure 4 illustrates the assessment phases performed within an LCA, in which first the goal of the assessment and its scope are defined.

The goal and scope definition stage is important for establishing the functional unit (the unit of assessment for the product/service being assessed), the scope of the assessment, such as allocation procedures, which life cycle phases are to be included (i.e. cradle-to-grave vs. cradle-to-gate, etc.), which impacts will be considered, assumptions, limitations, etc. With the goal and scope of the LCA established, the life cycle inventory (LCI) of the product/service can be developed through data collection and inventory analysis, in which the material, energy, and waste flows for each process within the life cycle are collected and assessed. With the LCI developed, the Life Cycle Impact Assessment can then be performed, where the inputs and outputs of the LCIs are connected to LCA databases and

[7] While LCA has primarily been used as a form of environmental assessment, life cycle thinking and assessment is also commonly used in Life Cycle Costing (LCC) as a form of life cycle economic assessment, and more recently to assess social impacts through Social Life Cycle Assessment (S-LCA). Moreover, a more recent development has been the transdisciplinary Life Cycle Sustainability Assessment (LCSA) method, incorporating environmental, social, and economic assessment all into the same assessment (Guinee et al. 2011).

the impacts of them are then applied to different impact categories where the results can then be interpreted as midpoints (which are cumulative categorial impacts of the different emissions, such as acidification or global warming potential) and endpoints (which can be described as the final estimated impacts in the cause-effect chain, such as to impacts to human health or forests for example). Finally, as an iterative process, the final step within the LCA process (and one that should be performed throughout the process) is the interpretation of the results, to provide the context and systemic understanding for the work performed in the LCA to ensure alignment with the project's goal and scope.

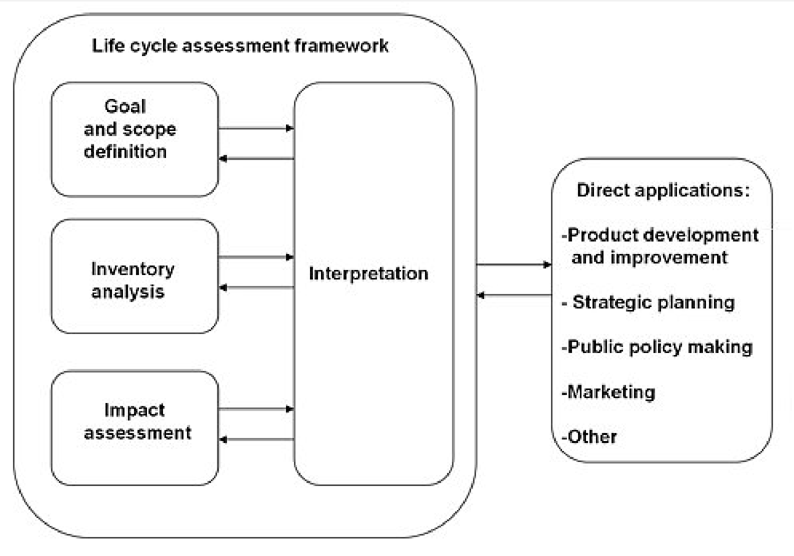

Figure 4. Phases within Life Cycle Assessment (Image taken from ISO 2006)

There have been a plethora of LCA studies performed comparing the environmental impacts of EVs and ICEVs, with a wide amount of variability. While other EV LCA review studies had been performed (Hawkin's et al. 2012; Nordelöf et al. 2012), these works reviewed studies 1997-2013, and with the rapid pace of technological developments, it appeared an updated review was needed. Marmiroli et al. (2018) provided an updated review, however, they placed a large focus on the electricity sources within the studies reviewed and highlighted the important role the modelled electricity source played in the final LCA results for EVs and the lack of methodological consistency found in the studies. With the focus on electricity sources, Marmoroli's research lacked a greater description regarding additional discrepancies between EV LCA studies, some of which were identified by Hawkin's et al. (2012) and Nordelöf et al. (2012), making it unclear if learning had occurred in the field due to the work of these reviews.

Paper I thus defined two research objectives[8] to address these research gaps (Dillman et al. 2020):

[8] Where research questions (RQs) are being used to signify the research questions posed by this thesis, and research objectives (ROs) are being used to the describe the research goals defined in the comprising papers, with the hyphenation used to represent the paper associated with the RO.

P1-RO1: How do the existing published LCA studies comparing EVs[9] and ICEVs, i.e., petrol or diesel vehicles, differ?

P2-RO2: How do the GHG intensities of the electrical grids across Europe affect EVs' environmental effectiveness?

Paper I used a systematic LCA review methodology to answer P1-RO1, and using the data collected through the systematic review, and meta-analysis was then performed to answer P2-RO2.

LCA Systematic review

A systematic review is the performance of a transparent and unbiased literature review using a clearly defined methodology. It can be done for a variety of purposes, such as providing critique, synthesizing information, generating opinions, or discussing data under different contexts (Neely et al. 2010). With the research goal of gaining a deeper understanding of the product level impacts of EVs and the causes for variability between EV LCA studies, a systematic review was the methodological approach selected, following an approach developed by Zumsteg et al. (2012) specifically for LCA reviews, which was adapted from the medical field's widely used PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) method (Moher et al. 2009). Following this methodology, Paper I was able to provide commentary on the three primary causes of variation and bias between LCA studies.

LCA meta-analysis

With the qualitative systematic review used to answer P1-RO1, Paper I then answered P1-RO2 through the use of LCA meta-analysis using the articles and supporting context provided by the review. First established by Glass (1976), meta-analysis refers to a method of "analysis of analyses", in which a large data set of results from individual studies can be integrated and analyzed statistically, answering new questions with a large set of secondary data. One of the challenges associated with performing a meta-analysis with LCA data can be the "harmonization" of the data due to the potential of different scopes and parameters used within the different studies (Arvizu et al. 2011). This challenge was also a strength of Paper I, as data harmonization allowed for the analysis of previously-incomparable data, thus supporting a novel assessment of the LCA data. This harmonization was performed by extracting disaggregated life cycle phase emissions from each study, and ensuring all assessments were converted to gross emissions [where if the data was provided using the functional unit, the results (often provided in gCO_2e/km) were then converted by multiplying the per functional unit results by the lifetime of the vehicle (kilometres)]. Each life cycle phase then had its own data set per vehicle type. Using this data, multiple GHG environmental breakeven points were calculated to answer P1-RO2.

Additionally, a Monte Carlo Simulation was run in python using the meta-data extracted from the review as statistical data to estimate the probability that an EV would lead to less life cycle emissions than a comparable ICEV over the lifetime of the vehicle. Using a normal distribution of the life cycle emissions for each phase, the total life cycle emissions per vehicle type were simulated 100,000 times across a range of electrical grid GHG emission

[9] It is worth noting that all references to EVs within Paper I refer to battery electric vehicles (BEVs); while plug-in hybrid electric vehicles (PHEVs) and fuel-cell electric vehicles (FCEVs) are an interesting field of study, they were considered outside the scope of Paper I

intensities to determine the probability that an EV would lead to less life cycle GHG emissions than the compared ICEV.

2.3.2 Paper II: Methods and research design

Dillman, K., Czepkiewicz, M., Heinonen, J., Fazeli, R., Árnadóttir, Á., Davíðsdóttir, B., & Shafiei, E. (2021d). Decarbonization scenarios for Reykjavik's passenger transport: The combined effects of behavioural changes and technological developments. *Sustainable Cities and Society,* 65, 102614.

Received 7 September 2020; Received in revised form 16 November 2020; Accepted 17 November 2020; Available online 22 November 2020

With the product level implications of EVs understood, discerning their urban level mitigation potential in decreasing transportation emissions and the role they have to play in urban development was the next topic of interest. With the vehicle life cycle thinking comprehension provided by Paper I, the importance of considering both direct and indirect GHG emissions when considering urban scale GHG emissions from the ground transportation sector was clear, a perspective which has been noted as lacking in national and urban inventory estimates in the literature (Chester and Horvath 2009; Croci et al. 2017). Often, when estimating the direct emissions associated with transport, a production-based approach is taken in which only the emissions which occur in the location under consideration are included, which can lead to carbon leakage and displacement of emissions to other locations (Seto et al. 2014). Thus, through a life cycle perspective, a consumption-based approach can be taken and disaggregated by direct and indirect emissions providing a broader perspective between the city and national inventories and the additional consumption emissions associated with the transport sector.

Many modern discussions surrounding approaches to transport decarbonization development follow essentially three development pathways, namely, low mobility, shared mobility, and e-mobility (Holden et al. 2019). These pathways generally fit the Avoid-Shift-Improve strategies, respectively. In the literature, the Avoid and Shift strategies broadly comprise what is referred to as demand-side solutions, and the Improve strategy is commonly referred to as supply-side solutions, where EVs are often considered the leading supply-side solution for urban transport[10]. However, as pointed out in the literature, IPCC analysis and other published transport GHG assessments often place a larger focus on technological approaches as opposed to behavioural approaches (Creutzig et al. 2016; Creutzing et al. 2018). While this may occur for a variety of reasons -- including the prominence of specialization in technological developments, the easier quantification and modelling of technological developments, or the less challenging political implication of implementing technologies versus behavioural/lifestyle changes -- it is clear that two approaches are often siloed in future-looking environmental assessments (Creutzig et al. 2016; Brand et al. 2019 Keyßer and Lenzen 2021).

[10] These two supply- and demand- side categories were labelled as behavioral and technological approaches in Paper II, respectively and thus will be referred to as such in this thesis.

Thus, taking the two direct/indirect and behavioural/technological perspectives into account, Paper II developed the following research objectives, using the city of Reykjavik as a case study:

> **P2-RO1:** Develop storylines that act as plausible decarbonization pathways for Reykjavik's urban mobility sector.
>
> **P2-RO2:** Perform both a direct and indirect GHG analysis for the city's daily travel demand, disaggregated by the passenger vehicle, bus, and Mobility-as-a-Service fleet.
>
> **P2-RO3:** Perform decomposition analysis determining which factors played the largest role in increasing or decreasing emissions within each scenario

Reykjavik provided an interesting case study for both Paper II and this thesis given its focus on EVs, where the city has a highly decarbonized electrical grid, some of the highest levels of car ownership in Europe, and Iceland has the second-highest penetration rate of EVs globally behind Norway.

When developing scenarios to model different development pathways from a certain perspective, there are essentially two approaches that can be taken: 1) forecasting (which is more typically paired with explorative approaches) and 2) a backcasting approach (which is typically a normative approach) (Van Vuuren et al. 2012). Whereas forecasting attempts to understand what is likely to occur using previous data and expected changes, backcasting is used to deduce how a desirable future could be attained (Robinson 1990). Alternatively, backcasting is a useful approach when dealing with complex, long-term issues such as technological development and societal changes (Dreborg 1996) and is particularly useful in sustainability assessments when attempting to understand how a societal transition towards a desired outcome can be achieved (Vergragt and Quist 2011). Thus, to understand the "What-if" implications of long term behavioural and technological development pathways, backcasting was the approach used within Paper II.

To interpret the impacts of long-term societal and technologically change scenarios as well as understand what political, societal, and behaviour forces would be required to achieve the backcasted scenarios of interest, the dual challenge existed of developing both a quantitative model and qualitative storylines that are consistent with each other. To harmonize the linguistic descriptions of the scenarios and the quantifications of the storylines, the Story-and-Simulation approach was used. Call-out Box 2 describes this approach in greater detail.

Call-out box #2: Story-and-Simulation Approach

The Story-and-Simulation (SAS) approach was formalized by Alcamo (2001; 2008), and, in his proposal, he suggested a 10-step iterative process for qualitative storyline and harmonized quantitative model development. The goal of the SAS methodology was to synergize the benefits of linguistic storylines and quantitative models for the development of better scenarios.

The benefit of qualitative storylines rests with their ability to take a multitude of viewpoints and perspectives and put them together into understandable storylines that can potentially provide a more engaging communication about the future than solely quantitative models. They are useful for the development of complex and long-time scale possible futures that may be difficult to manoeuvre towards solely using numbers without the added descriptions. The drawbacks of storylines, however, are by definition their inability to capture quantitative results and the difficulty in reproducing them, a keystone of the scientific method (Pedde et al. 2019).

Quantitative models on the other hand have the benefit of providing oft-desired numerical results which are considered to be more transparent due to the ability to trace the variables and equations which lead to the results, which additionally allows for reproducibility. Their weakness lies, however, at times in the false-knowing provided by the exact numbers in which quantitative results are often expressed and in the assumptions made within the model, which derived by the modeller could lack a realistic reflection of what would actually occur, following Box's (1987) aphorism, "all models are wrong but some are useful".

Between quantitative and qualitative scenario approaches, there exist hybrid approaches such as fuzzy set models/theory, storylines interspersed with quantitative data, system dynamic models supported by qualitative data, Cross-Impact Balance, and of course the SAS approach. These hybrid methods seek to take advantage of the benefits of both quantitative and qualitative approaches, though all with their own pitfalls. The challenge then exists in selecting the best approach for the task at hand.

Two of the most notable pitfalls of the SAS approach are reproducibility and conversion problems. The reproducibility problem arises from the difficulty in reproducing the results from qualitative storylines and stakeholders, where there will always be a deficit from the entirety of the implicit knowledge within all stakeholders who assist in developing the scenarios and the information contained within developed storylines (Alcamo et al. 2008) and due to the lack of explicitness inherent in narratives (Pedde et al. 2019). There are techniques available and studies performed to address the reproducibility issue such as mental models, causal diagram development, and other such methods for group model building (Rao Mallampalli 2016; Voinov and Bousquet 2010). These, however, can quickly become overly complex to the point of meaningless and thus modellers and stakeholders should work to ensure as much transparency whilst maintaining as much meaning as possible.

The second problem, that of conversion, can be described as the difficulty in harmonizing the linguistic qualitative storylines and quantitative modelling, where a consistent conversion from verbal description to numerical data proves to be a difficult task (Pedde et al. 2019). This difficulty presents itself in both directions, in which converting scenario textual descriptions of changes to numerical data lacks transparency and, as well, when the numeral results of the model are prepared, converting them into a logical storyline of results again lacks reproducibility and transparency. Solutions to the conversion problem include translation keys and centre-of-gravity modelling, amongst others as a way to categorize defined verbal descriptions into numerical values (Alcamo 2008).

Even with these pitfalls, the SAS approach has proven to be a robust approach used in a variety of global GHG emissions and energy transition models (Li et al. 2015). To develop a normative set of backcasted scenarios that would reflect socio-economic, political, and technological changes, in Paper II it was thus decided that SAS would be the approach of choice, and an adapted version of Alcamo's 10 step process was used, as shown in Figure 5.

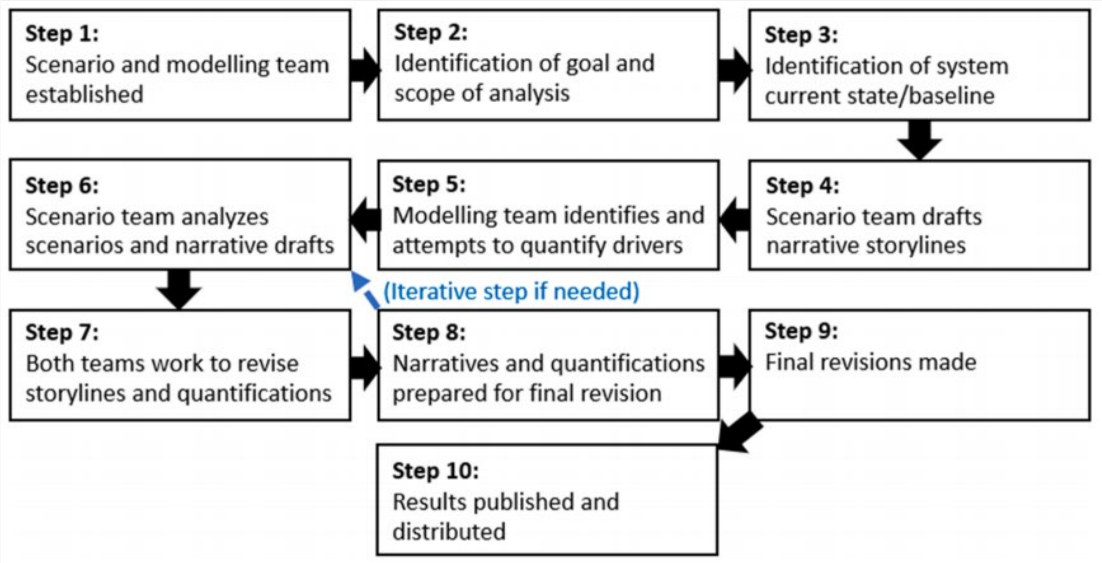

Figure 5. Steps in Paper II followed to perform Modified from Alcamo's (2008) SAS method. Image taken from Paper II.

A two-axis approach guided the development of storylines that explored the comparative impacts of strictly behavioural, technological, and integrated approaches. Greater detail surrounding the scenarios both qualitative and quantitative can be found in Paper II. Figure 6, however, provides an illustrative look at where the scenarios modelled fit along the behavioural and technological development pathways with a brief description of the major changes occurring in each scenario.

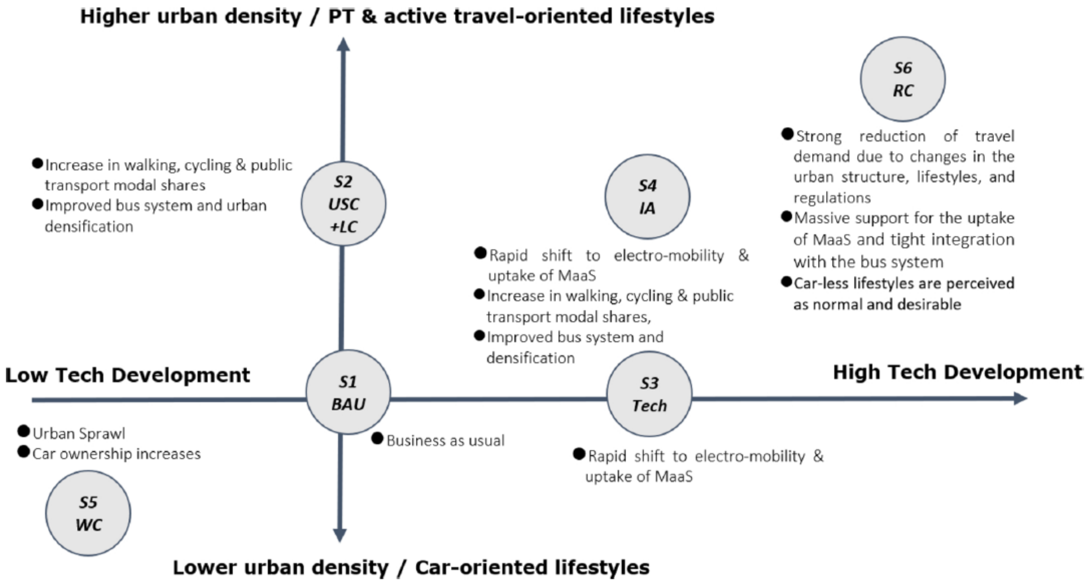

Figure 6. The 2-axis behavioural/urban form and technological changes framework and mapped scenarios within it. Image taken from Paper II.

After developing scenario storylines, the next step was to quantify the emissions from the urban passenger mobility sector for each scenario. To avoid redundancy, this thesis guides those interested in reviewing the calculations in greater detail to Paper II within this thesis, and for this summary, Figure 7 provides a conceptual depiction of the calculations.

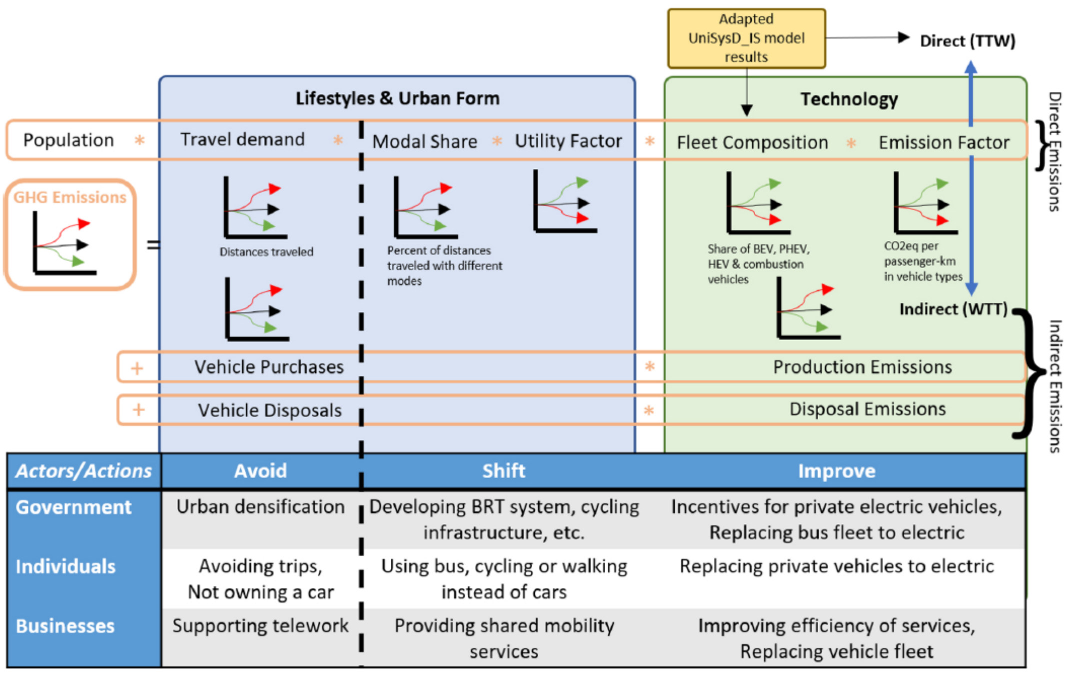

Figure 7. Model of modified Kaya identity direct GHG estimations for a transportation sector combined with indirect GHG emission calculation methodology. This model

conceptually grouped the 2-axis behavioural/urban form and technological changes framework used within this study

The direct and indirect emissions associated with the Tank-to-Wheel (TTW) and Well-to-Tank (WTT) emissions were estimated using the Kaya identity, a well-established top-down approach for estimating GHG emissions (Kaya, 1989). Paper II additionally estimated the embedded emissions associated with car fleet turnover using the life cycle phase emissions estimated in Paper I as well as results from additional studies (such as life cycle impacts of different bus types, etc.). The direct emissions estimate from urban transport was associated with the TTW emissions and the indirect emissions estimate was composed of the WTT, production, and disposal emissions.

The blue box in Figure 7 illustrates behavioural changes induced by changes to urban form and lifestyles such as reduced travel demand, increased shared/active transport modal shares, increased utility factors through ride-sharing and increased public transport ridership, and levels of car ownership (which is a key determinant of annual car purchases and disposals). The green box encapsulates the Kaya identity variables associated with technological changes within Paper II, namely fleet composition, emission factor, and the production and disposal emissions, with all variables per vehicle type by mode type. The small graphs near each variable show the variable direction (increase or decrease) that would lead to less GHG emissions.

Lastly, to fulfil P2-RO3, a decomposition of the results was needed. The well-established Log Mean Divisia Index (LMDI) method developed by Ang and Liu (2001) was used to perform the decomposition. While the details of the calculations can be found in Paper II, worth noting in this summary is the novel adaptation of the LMDI, which was required due to the addition of sums between the TTW, WTT, production, and disposal emissions, where a layered LDMI process was required. The change in emissions from each of these emission categories had to be decomposed separately and then added together to estimate the final change in emissions from year *0* to year *t*. This was an additional step that had not been seen in previous LMDI examples or literature.

2.3.3 Paper III: Methods and research design

Dillman, K. J., Fazeli, R., Shafiei, E., Jónsson, J. Ö. G., Haraldsson, H. V., & Davíðsdóttir, B. (2021a). Spatiotemporal analysis of the impact of electric vehicle integration on Reykjavik's electrical system at the city and distribution system level. *Utilities Policy*, 68, 101145.

Received 6 April 2020; Received in revised form 16 November 2020; Accepted 16 November 2020, Available online 31 December 2020

With the understanding provided by Paper II of the GHG emissions associated with the urban mobility sector and development pathways, Paper III then sought to investigate another city-level impact associated with EV integration and market development, namely, the impact of EV integration on the city's electrical grid and, in particular, their potential impact to the city's peak load. Reykjavik was again used as a case study, due to the city's already relatively strong market presence of EVs globally, political support of the necessary infrastructure development (Ministry for the Environment and Natural Resources 2020; City of Reykjavik

2016), and a small-enough population that allows more rapid infrastructure changes as compared to more heavily-populated locations.

Multiple studies have noted that much of the focus surrounding the impact of EV[11] integration to a city's distribution system typically emphasizes the peak load impacts to the system as a whole and the electrical capacity to support the added demand. However, there is a growing consensus in the literature that impacts to local distribution networks (i.e. substations and other sub components of an electrical system) will likely be overwhelmed before the aforementioned systems (Short and Denholm 2006; Liu et al. 2011; Clement-Nyns et al. 2011; Waddell et al. 2011; Brady and O'Mahony 2016). Thus, with Reykjavik looking towards a variety of EV-supporting tax incentives, Paper III established its research objective as:

> **P3-RO1:** The performance of a case study on the impact of the integration of EVs impacted by different pro-EV policies on the electrical grid at a system and subsystem level, temporally and spatially.

Accomplishing the research objective at multiple levels of spatial granularity required an appropriate assessment method. Figure 8 provides a conceptual overview of the temporal and spatial requirements for different assessment types (Daina et al. 2017). The top-right quadrant represents the spatial and temporal scale needed to assess both city and distribution level grid impacts and reflects the obvious need to consider the daily load added by EVs that could potentially impact the peak load on a distribution system.

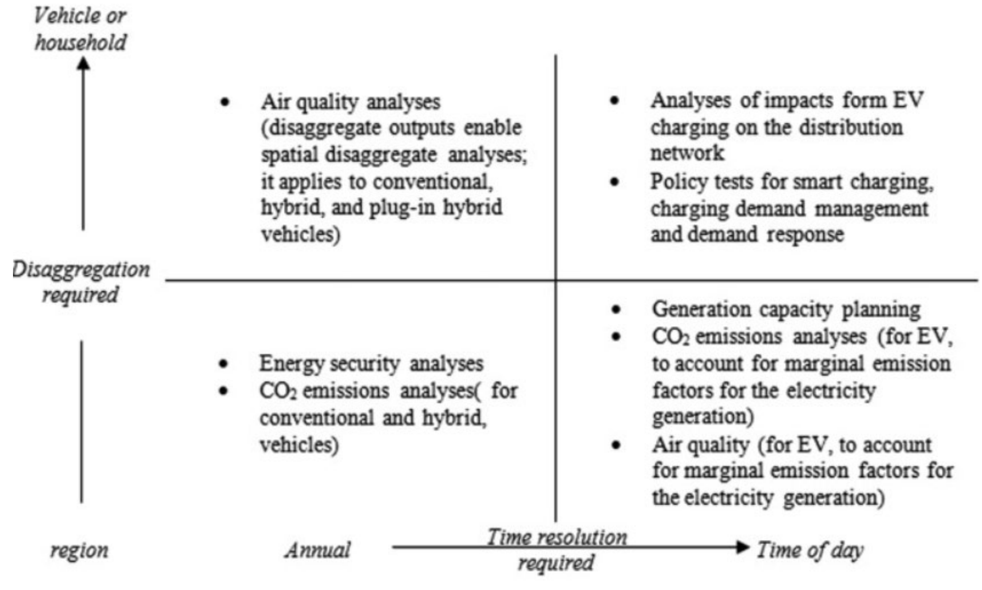

Figure 8. Spatial aggregation levels and time resolution in EV use models required by the analysis purpose (image and caption from Daina et al. 2017)

Reviewing the field of methods for such an analysis, it was clear that a short-period model was needed for the desired spatial and temporal granularity. With the Gallup (2017) activity-based survey data available with over 23,000 activities and 6,000 respondents from the Reykjavik area, an activity-based model was determined to be the most appropriate method

[11] It is worth noting that in Paper III the impact of both EV and PHEV integration were taken into account.

for the analysis. With the method of assessment selected, the next step was to operationalize the assessment method. Paper III provides greater detail on the method followed, however, Figure 9 provides a flow chart of the analysis performed, and a synopsis of the method follows here.

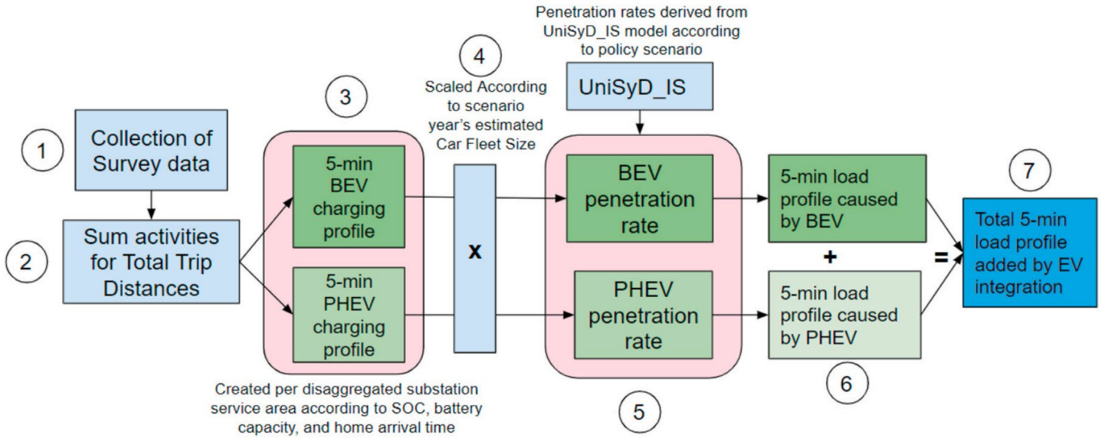

Figure 9. Flow chart of the activity-based approach. (Image taken from Paper III).

First, the Gallup (2017) activity survey data was analysed to develop the activity-based model. This model was then adapted to develop a 5-minute BEV and PHEV charging profile, where according to the total travelled per each respondent's trip chain of activities upon arriving home, the state of charge of the modelled BEV/PHEV's battery was estimated and the necessary charge time and electricity demand determined according to the model's assumed charger capacity. An assumption of uncontrolled home charging for all users was used to develop a worst-case scenario. This assumption was intentionally used to consider where and when grid risks could occur without charging behaviour intervention as opposed to attempting to model the exact potential charging profile. Subsequently, according to the city's estimated fleet size (allocated by substation service area population) and BEV/PHEV penetration rates per policy scenario, estimated using Shaffiei et al.'s (2015; 2019) UniSyD_IS system dynamics model, the 5-minute load profile from BEVs and PHEVs were determined. Summing these two load profiles, the total load profile from EV integration was estimated.

2.3.4 Paper IV: Methods and research design

Dillman, K., Czepkiewicz, M., Heinonen, J., & Davíðsdóttir, B. (2021c). A Safe and Just Space for Urban Mobility - A Framework for Sector-Based Sustainable Consumption Corridor Development. Global Sustainability, 1-42.

Received: May 31st, 2021 / Status: Manuscript Accepted with Major Revisions

With the urban-level perspectives provided by Papers II and III, the field of Sustainable Urban Mobility (SUM) indicators was identified as the next potential field of interest for study, with a potential desire for performing a case study on Reykjavik to assess how sustainable the city's current mobility system is and how the integration of EVs plays a role in improving these indicators. However, upon review of relevant studies and over 250 SUM indicators, a clear pattern emerged in which, while many measurements of different facets of sustainability in the transport sector existed, there was a clear lack of a definition of an intergenerationally sustainable state for the urban mobility sector (Dillman et al. 2021b). Holden et al.'s (2013) SUM indicator initiative echoed these findings, where they highlight the importance of the use of thresholds as opposed to rate of change indicators and where they emphasize, "Changing a non-sustainable state to a less non-sustainable state is positive, but the result cannot be regarded as sustainable". Exploring this further, it became clear that an intergenerationally sustainable system state for the urban transport sector had yet to be defined. Identifying this gap in the literature, the research objectives for Paper IV were defined as:

> **P4-RO1:** Provide a first iteration towards developing a framework assessing the progress of the transformation to a 'safe and just space for the urban mobility sector' bound by an integrated ecological ceiling and a social foundation
>
> **P4-RO2:** Through the framework developed in RO1, provide commentary on existing SUM indicators and their general lack of connection to thresholds.

The first step towards answering these questions presents the obvious question, what does it mean for an urban mobility system to be intergenerationally sustainable? To answer this question, Paper IV looked towards the 'doughnut economics' (Raworth 2012; 2017) and SCCs (Di Guilio and Fuchs 2014; Fuchs et al. 2021) frameworks for inspiration.

With humanity's transgression of the Planetary Boundaries (Steffen et al. 2015) and the approach of 'Peak Everything' (Heinberg 2010), there is growing consensus in some academic circles that the only way forward is one of 'strong sustainability'. This will require reduced consumption in absolute terms (Lorek and Fuchs 2019) as well as the de-escalation (Brand-Correa et al. 2020) and degrowth (Spagenburg 2014) of economies, institutions, and need satisfaction/consumption behaviour such that we can consume within the EC's presented by the PBs. In this line of thinking, it is clear that, to define an intergenerationally sustainable state, the presence of an EC is necessary.

Intergenerational sustainability additionally contains the equally important social pillar. Building off the UN's Universal Declaration of Human Rights objectives of "relieving people of the fear of poverty and deprivation" and the "recognition of the inherent dignity and of the equal and inalienable rights of all members of the human family is the foundation of freedom, justice and peace in the world" (UN, 1948), there has been significant work done to develop Social Foundations such that all humanity would have the ability to live such a dignified life (e.g. ILO 2011; Raworth 2012; Spagenburg 2014; Lucas et al. 2016; Fuchs et al. 2021). Pereira et al. (2016), for example, has mapped what such social justice approaches exist for the transportation sector.

Integrating these two thoughts, it was determined that an intergenerationally sustainable urban mobility sector would consist of an EC and SF relevant to the environmental impacts of the mobility sector and the social implications of urban passenger transport. There exist examples of the applications of integrated EC/SF frameworks globally (Raworth 2012; Raworth 2017; Millward-Hopkins et al. 2020), at a country level (Dearing et al. 2014; Rao et al. 2019), and at a city level (Raworth et al. 2020). There additionally have been calls to develop sector-level 'safe and just' spaces (Fuchs, et al. 2021). The EAT-Lancet Commission (2019) provided such an example of what could be viewed as a 'safe and healthy' space for the nutrition sector. Many studies have identified mobility as a key lifestyle sector that could have the greatest ability to reduce GHG emissions (Akenji et al. 2019; Ivanova et al. 2020; Shigetomi et al. 2021), but there have not been any studies developing an SCC for the mobility sector. Additionally, while multiple studies explain SCCs conceptually and their importance (Di Guilio and Fuchs 2014; Spagenburg 2014; Fuchs et al. 2021), how to operationalise the concept sectorally becomes more ambiguous.

Thus, Paper IV established an initial concept for the characterization of a sector-based SCC, illustrated in Figure 10. For greater detail of each step, please refer to Paper IV.

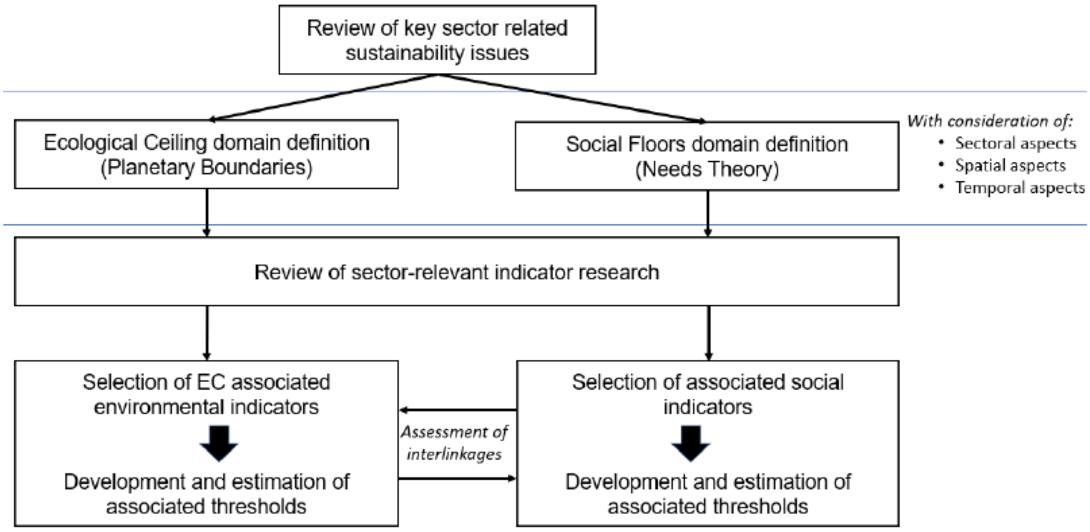

Figure 10. Framework for the development of a sector-based Sustainability Consumption Corridor (Image and capital taken from Paper IV)

As a first step towards sector-based SCC development, following thoughts on SCC development by Fuchs et al. (2021, pgs. 48-49), a review of key sector-related sustainability issues was suggested to gain a greater systemic understanding of the relevant social and environmental impacts of the sector, with an understanding of the materiality issues, life cycle impacts, relevant actors, and needs and satisfiers which exist within the sector. The next step was then to place these issues within the context of ECs and SFs. The PBs act as a useful framework for establishing an EC, though Paper IV discusses the variety of challenges associated with spatially, sectorally, and temporally applying them. In this step, the environmental impacts relevant to the sector explored during the review can then be applied to the PBs to establish a set of relevant environmental domains to which the thresholds can be applied.

In this step, the same process should be followed for establishing the SF. Unlike the EC, however, there are no PBs or globally agreed-upon SFs which can act as an endpoint for all sectors. For example, GHG emissions across sectors all impact the climate change PB, however, while Raworth (2012) did provide a set of SFs, they are global and spread across many sectors, making it difficult to provide granular SF guidance. Paper IV describes these issues in greater depth, but of note here is SFs' capacity to be more quantifiably difficult due to challenges measuring well-being as opposed to parts per million in the atmosphere, such as is the case for climate change. Additionally, worth expanding upon is the approach to address the difficulty in developing the SFs to understand what is needed to sectorally provide a 'dignified' and 'good' life. Many of the discussions surrounding the development of a SF are based on the understanding that all humans have the right to a dignified life and to have their basic needs met. Well-being, needs, and needs satisfaction are both ancient and currently relevant fields of study, and thus Call-out box 3 describes some of the historical and differing fields of thought on the topic.

Call-out box #3: Well-being, Human Needs, and Needs Satisfaction

The desire to understand human happiness and well-being has been a central thought within the human experience, one that has been questioned, interpreted, and explored for thousands of years (Pawelski 2013). Through this prolonged investigation, two relatively distinct central viewpoints of happiness have emerged, the hedonic and the eudaimonic perspectives. From a hedonic point of view, the goal of life and derived happiness stems from the maximization of pleasurable and minimization of painful experiences (Kahneman, 1999; Diener 2000). Some utilitarian perspectives from the likes of Bentham suggest that a good society itself is built from individuals' self-interest and desire to maximize their own pleasures (Ryan and Deci 2001). This thought of utility aligns with classical economics' association of needs satisfaction to individual utility (Smith, 1776). However, more modern neoclassical economics (with some exceptions) has slowly disassociated this connection to human needs and needs satisfaction, instead equating utility to the satisfaction of 'wants', where the difference between a need and want is no longer distinguishable (Georgescu-Roegen 1973; Lux and Lutz 1988). Where needs can be seen as finite, human wants are often seen as infinite and insatiable, where elasticity can attempt to measure a willingness to pay regardless and use this as a scale to identify a need versus a want (McConnell 1981, p.23; Anderton 2000, p.3). This insatiability can be perceived through the modern economy's turn towards an economy of bigger, faster, farther which has thus escalated resource and energy use, which have led humanity towards its current environmental predicament (Lamb and Steinberger 2017).

Countering the hedonic point of view is the eudaimonic perspective, which finds the search for happiness through the fulfilment of desires to be a misdirected effort of human existence, and that rather happiness is distinct from well-being, and the pursuit of well-being is the more virtuous direction (Fromm, 1981). From the eudaimonic perspective, the fulfilment of every desire may not lead to the improved well-being of an individual, and, thus, while hedonic pleasure may correlate with eudaimonic well-being, they are not always aligned (Waterman 1993). While there are multiple interpretations of eudaimonic well-being, all of them incorporate a perspective of certain unquestionable human needs, which allow for physiological health and additional aspects of self-realization and social fulfilment and inclusion, and are approaches which differ significantly from the hedonic perspective (Ryan and Deci 2001).

Through this perspective and its acknowledgement that humans inherently have a set of finite attainable needs, two questions present themselves: 1) What are these inherent universal needs? 2) How do we satisfy these needs such that eudaimonic well-being can be achieved? There have been multiple sets of needs provided by the literature to answer the first such as Maslow's (1943) well-known hierarchy of needs [for examples of needs sets see: Max-Neef et al. (1991); Nussbaum and Sen (1993); Di Giulio and Defila (2019); Doyal and Gough (1991); Costanza et al. (2007)]. While the number of needs, their hierarchy of satisfaction, and their definitions may differ, all of them acknowledge a finite set of needs that can be met which would allow for eudaimonic well-being. For example, using Goyal and Gough's (1991) needs perspective (which was the perspective employed in Paper IV), basic needs (e.g., critical autonomy, physical health) are differentiated from intermediate needs (nutritional food, appropriate healthcare, etc.), which are then distinct from needs satisfiers (transport, friendship, employment, etc.).

What kinds of satisfiers are available and employed answers the second question posed, and how effectively they satisfy people's needs is largely dependent on structural aspects, such as social relationships, institutions, infrastructures, etc. (Mattioli 2016, Gough 2017). The satisfaction of existential human needs, such as hunger and thirst, included in all needs theory discussions undoubtedly requires some form of consumption. This is where consumption choice and access to choice play a role, and how needs are satisfied intersects with sustainability considerations (Brand-Correa and Steinberger 2017; Gough 2020). For example, in Brand-Correa et al.'s (2020) work, they use the private car as an example of escalating need-satisfaction, where previously transport needs may have been met by less energy and material intensive means such as electric trams in one example by Brand Correa et al., private cars have increasingly been seen as a need in order to meet transport needs. This greater requirement of a private car represents an escalation of needs satisfaction, as the satisfaction of the need requires a greater amount of materials and energy than previously sufficing choices. This example serves to illustrate the relevance of well-being, needs theory, and needs-satisfaction to sustainability discussions.

From the economic perspective, the eudaimonic well-being viewpoint thus counters the idea of an infinite set of bigger, better, faster, and more wants and instead places a focus on the sufficient meeting of needs required to live a 'good life'. This idea of sufficiency aligns with the degrowth movement (Kallis 2011; Kallis et al. 2012) and the decoupling of GDP and well-being (Kubiszewski 2013). Thus, by challenging the modern economic paradigm of indefinite GDP growth, an economic model based on eudaimonic well-being can focus on the meeting of human needs without indefinite consumption, frequently making this the perspective of choice in SCC discussions.

SCC and good life studies often relied upon the eudaimonic perspective due to its focus on well-being and self-actualization through the satisfaction of human needs. Taking this viewpoint, we suggest the application of needs satisfaction theory relevant to the mobility sector, an approach which has been noted as lacking in the literature for the mobility sector (De Vos et al. 2013). It is recognized that there are limitations to the approach, both for the use of needs theory in general, as well as its application in studying mobility. Similar to the critiques of Maslow's hierarchy, where doubt is cast on the pure objectivity of human needs, other such approaches to develop universal needs can be subject to critique regarding their ability to subjectively consider social and cultural interaction with said needs (Trigg 2007), to incorporate gender and age differences in needs (Hofstede 1984; Tay and Diener 2011) and to differentiate individualist versus larger collectivist and community needs perspectives (Hofstede 1984; Cienci and Gambrel 2003). Further, specifically for mobility, deciphering between needs and wants can be challenging, where mobility is not always derived demand, but can also have its own intrinsic value [whether for speed, admiration of beauty or nature, etc. outside of trips considered mandatory for maintenance, see Mokhtarian and Salomon (2001)].

However, needing a place to start to take the first steps towards developing a more actionable sectoral SCC, we used the eudaimonic approach as the basis for development. It was suggested that this sectoral perspective should additionally take spatial, temporal, and cultural aspects (amongst others) into account when developing the SF, as well as the EC, though particularly for the SF as setting the SF can be quite nuanced in terms of what is considered sufficient according to these different contexts. This holds especially true for the mobility sector, which does not satisfy a need in itself, but rather provides the means for people to meet their needs. As such, making generalizations towards an approach to transport in the different contexts is particularly difficult. For example, what may be an acceptable distance in a sprawled context could vary significantly from a highly dense context. Alternatively, different levels of car ownership may be considered acceptable, particularly in different Global South and North contexts. The results of this work for the mobility sector will be discussed in the following section.

With the ECs and SFs established, Paper IV was then interested in characterizing the SCC through the use of indicators. A published set of SUM indicators from Sdoukopoulos et al.'s (2019) review was used to take a first step in doing so, associating these indicators to the EC and SFs. This provided a good context for discussing indicators relevance to the associated thresholds and issues with indicators which could potentially have competing goals in certain contexts (i.e. the use of car ownership both as a social indicator indicating accessibility as well as an environmental indicator, where an increase would represent greater environmental impacts). Examples of the thresholds and potential indicators were then provided as the final results to give a final characterization of the SCC.

3 Results

The results of the four papers which comprise this thesis are reviewed here following the multi-scale approach presented in Figure 2, where first the product level results are discussed, followed by urban level results, and concluded with the global intergenerational perspective provided by Paper IV. With the multi-scale results reviewed, these results were then integrated to provide the overarching results of the thesis. Finally, for greater detail, the individual results from each paper relevant to the thesis are then described.

3.1 Main Findings

Starting at a product level, while the review in Paper I found room for improvement in EV LCA methodologies (such as methodological, goal, and scope differences; varying assumptions and contextual differences; and different levels of data availability and granularity of the data between studies) the results of the meta-analysis were quite conclusive. EVs were found to generally have higher production emissions than ICEVs, and electricity grid GHG intensities played an important role in determining the final life cycle GHG emission outcomes of an EV. It was seen that EVs in nearly all grid contexts outperformed ICEVs, especially petrol vehicles: in the EV-diesel comparison, only in 6 countries across the EU -- namely Estonia, Latvia, Poland, Greece, Cyprus, and Malta -- was it found that using the current electrical grids, EVs would on average lead to more life cycle GHG emissions[12]. However, at higher grid carbon intensities, the GHG benefit from EVs becomes increasingly marginal. For example, whereas the emission disparity in Iceland was estimated to be approximately 22 and 40 $tCO_2eq.$, meanwhile, Germany was estimated to only have an emission disparity of 4 and 21 $tCO_2eq.$ for diesel and petrol vehicles, respectively. Thus, without continued electrical grid decarbonization, purchasing an EV vs a diesel vehicle in Germany would see marginal benefits from changing over to EVs. This is not to say that EVs would not provide GHG mitigation potential, but rather that according to the grid context, it is important to consider the extent of the mitigation that EVs can provide. A temporal assessment of these environmental breakevens relevant to the assumed annual use of the vehicle and decarbonization targets of regional grids was out of the scope of the study but would be a good area of future study.

Zooming out to the urban sector, GHG and grid impacts were the two primary urban perspectives investigated within Paper II, as they represent some of the most commonly discussed urban level implications of EV integration. From a GHG perspective, it was shown that, at an urban level, EVs could greatly decrease direct emissions due to the absence of direct (TTW) emissions. However, at higher car fleet sizes and associated turnover, this decrease in direct emissions could be partially offset by the increase in indirect emissions due to the higher embedded emissions from production emissions identified at the product level. This was shown in Paper II, where even in the Reykjavik scenario -- a city with a highly decarbonized electric grid providing a near-best case scenario for indirect energy use

[12] Using an estimated lifetime of 184,000 kilometres, the average lifetime for EVs and ICEVs across the review

impacts (WTT) leading to maximum GHG mitigation during the use phase when considering the direct and indirect emissions associated with EV integration -- the final result was similar and slightly worse to that of a more behavioural approach. Additionally, through Paper III it was shown that greater rates of EV integration without controlled charging will lead to increased grid impacts. This can lead to less grid reliability and a need for greater system capacity.

Following the exploration of urban level impacts, RQ3 then sought to understand how a SCC could be characterized for the passenger urban mobility sector and considered potential domains and indicators to define such a corridor. Paper IV developed a framework to accomplish this research goal and suggested an initial set of domains for the ECs and SFs, provided feedback on existing SUM indicators, and assisted in characterizing a mobility-focused SCC. This work provided multiple interesting results. First and of key importance was the identification of the weakness of SUM indicators' current lack of threshold ties and the existence of a subset of indicators with conflicting sustainability goals, often relevant to the context of their implementation. Second was the sector-relevant characterization of the EC and SFs, which has been called for in the literature (O'Neill et al. 2018), where the ECs were characterized using the PBs and the SF using a needs-satisfier chain approach.

Integrating these results, first at an urban level, it can be seen that increased integration of EVs (as compared to a BAU scenario with ICEV prominence) without fleet size reductions will lead to decreased direct emissions, increased indirect emissions (due to the higher embedded emissions identified in the product level assessment), and an increased peak load (among other impacts to the electrical grid), which could stress the electrical distribution system. Worth inspection within this integrated perspective is the importance of not just EV integration rates, but also total fleet size. A decrease in total fleet size would decrease the negative impacts associated with EV integration from both the GHG and electricity demand perspectives. For example, from the GHG perspective, a smaller vehicle fleet would lead to subsequently less vehicle turnover, which would lead to fewer EVs needing to be produced and thus fewer indirect emissions. From the grid impact perspective, the impacts to the grid are, of course, due to the gross amount of EVs charging their batteries, not the rate of integration. Thus, the smaller the vehicle fleet, the greater levels of integration rates could be seen without leading to additional impact. A similar connection could be made with travel demand and travel mode shares. As shown in Paper II (particularly in the S2-behavioural change scenario, which isolates these transformations), reduced travel demand and increased model share of public transport and active transport modes would lead to less GHG emissions. Further, if one were to consider the travel behaviour model developed in Paper III, if this model were to consider greater use of public transport, active transport modes, and decreased travel demand and travel distance, this would likely be associated with less passenger vehicle and energy use (and for the model EV and electricity use), thus leading to less charging overlap and peak load impacts.

From the intergenerational sustainability perspective, these results highlighted the mutual need to bridge the fields of sustainable urban mobility, Earth system, and social provisioning studies. This bridge is relevant to this thesis both from an environmental and social perspective. Environmentally, the discussion surrounding EVs rarely includes intergenerational sustainability or the ability for EVs to allow humans to reside within the 'safe space' identified by the PBs. This makes the discussion surrounding the direct and indirect environmental impacts of EVs all the more relevant, because GHGs do not consider international borders, and while many urban and national plans discuss the need to address direct GHG emissions, staying within the PBs requires addressing global GHG emissions. For example, while placing thresholds on each of the domains (and sub-domains) was considered to be out of the scope of Paper IV, Figure 11 combined adapted results from Paper II[13] and placed them within the context of the level of consumption estimated by Akenji et al. (2019) that would keep warming below 1.5°C. This provided an interesting context for the Reykjavik case study, where it could be seen that, in almost all scenarios except the radical change scenario, the urban mobility sectors' consumption took significant percentages of a consumption budget that would allow for staying below 1.5-2C warming. For example, the results illustrated in Figure 11 estimate that by 2050, according to the EV-focused technological scenario, a person's transport consumption would consume nearly their entire 1.5°C friendly consumption budget (where the darkening red boxes represent this budget), leaving no room for emissions from other consumption sectors such as nutrition, housing, and goods and services. These results are only enhanced when one considers that additional electrical system capacity that would be required to support larger EV fleets.

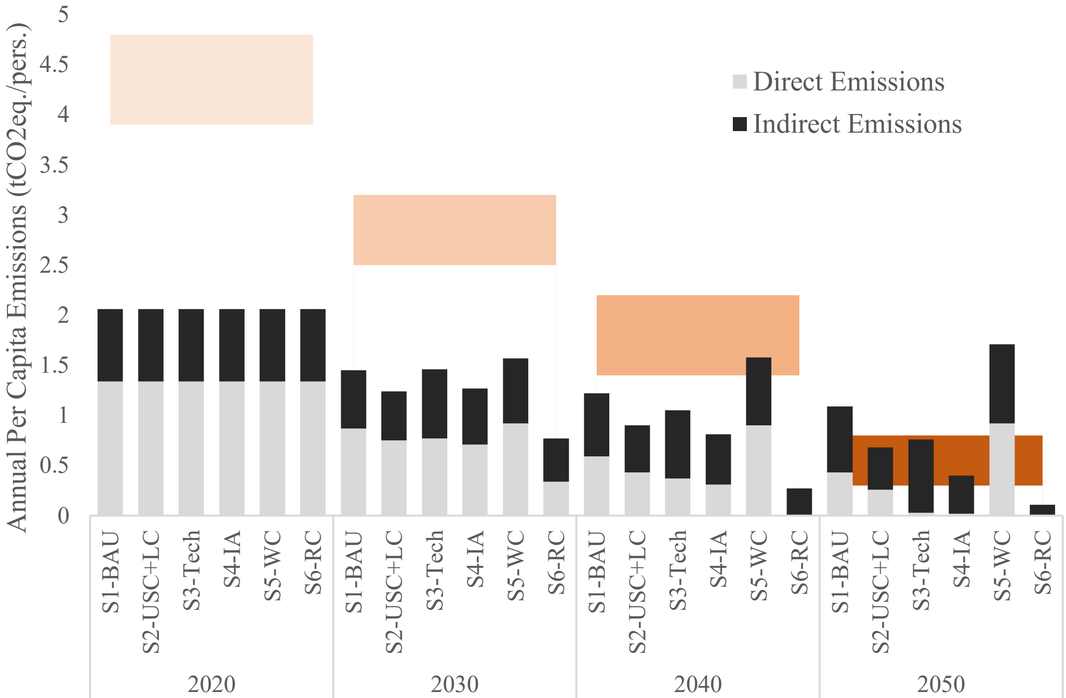

Figure 11. Estimated annual direct and indirect emissions from passenger transport per capita for each development pathway scenario considered in Paper II. The darkening pink boxes represent the threshold range of total per capita consumption emissions[14] during the associated year estimated by Akenji et al. (2019) that would allow for warming below 1.5°C.

Additionally, within this context of 'safe and just' sustainable urban development, the definition of the SF provides an interesting context for discussion. Firstly, the social and justice implications of high levels of EV integration need to be considered. For example, in

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[13] These adapted results divide the annual direct and indirect emissions from the associated year published in Paper II by the estimated population to get per capita direct and indirect GHG emissions ($tCO_2eq./pers.$)

[14] For all consumption sectors, not just mobility, where determining the sectoral allocation of emissions over time was considered to be outside of the scope of this paper.

Sovacool et al.'s (2019) energy justice assessment of the EV transition in Norway, injustices were found at the micro scale (increased car use leading to congestion, pollution, parking problems, avoidance of walking/cycling, and lack of infrastructure in rural area), meso scale (diversion of taxes from public transport, expansion of roads into environmentally sensitive areas, (greenwashing of national policy), and at the global scale (poor labour conditions foreign resource extraction, hazardous waste streams, exporting of dirty cars). Furthermore, the greater integration of EVs and associated energy demand from EV use can additionally lead to increased local grid costs if smart-charging strategies are not integrated (Wangsness and Halse 2021), potentially leading to increased transportation costs and energy/transport affordability/poverty (Mattioli et al. 2017).

Thus, with the dual environmental and social implications surrounding EVs, the conversation needs to move beyond the technological. Discussions surrounding the social need for transport and urban form perspectives are needed to supplement the often-lacking context of these issues in EV studies. In Paper IV's development of a mobility-focused SF, alternatively, a more directional approach was taken to mobility, where before thinking about technological solutions and mobility systems, it was considered that accessibility should be enhanced before enhancing mobility (where enhancing the first would work to reduce the latter). This needs satisfaction approach highlights the disparity and potentially errant perspective being taken in many international environmental transport initiatives which place a disproportionate focus on EVs. Figure 12 illustrates these two differing directional approaches within a needs-satisfier chain perspective, where it shows that taking an EV centric perspective is essentially taking a 4th order need-satisfier perspective. Alternatively, taking the accessibility approach described in Paper IV, starting from the basic need and moving down the line, if the solution were solved further up the need chain there could be less of a need for private vehicle transport and the potential for de-escalation could exist, as illustrated in Figure 12. De-escalation in this case refers to a decrease in material and energy use required to satisfy transport and the associated need that the transport system is servicing. This approach to transport has implications across the thesis, where the behavioural approach taken in Paper II can be more easily compared to the accessibility approach in which first travel demand and modal shares were addressed and then emissions factors, as opposed to the opposite through the more EV-focused technological approach. These integrated results will be interpreted later in the Discussion section, and the following subsections will provide a detailed overview of the results from each individual paper, which led to the conclusions of these integrated results.

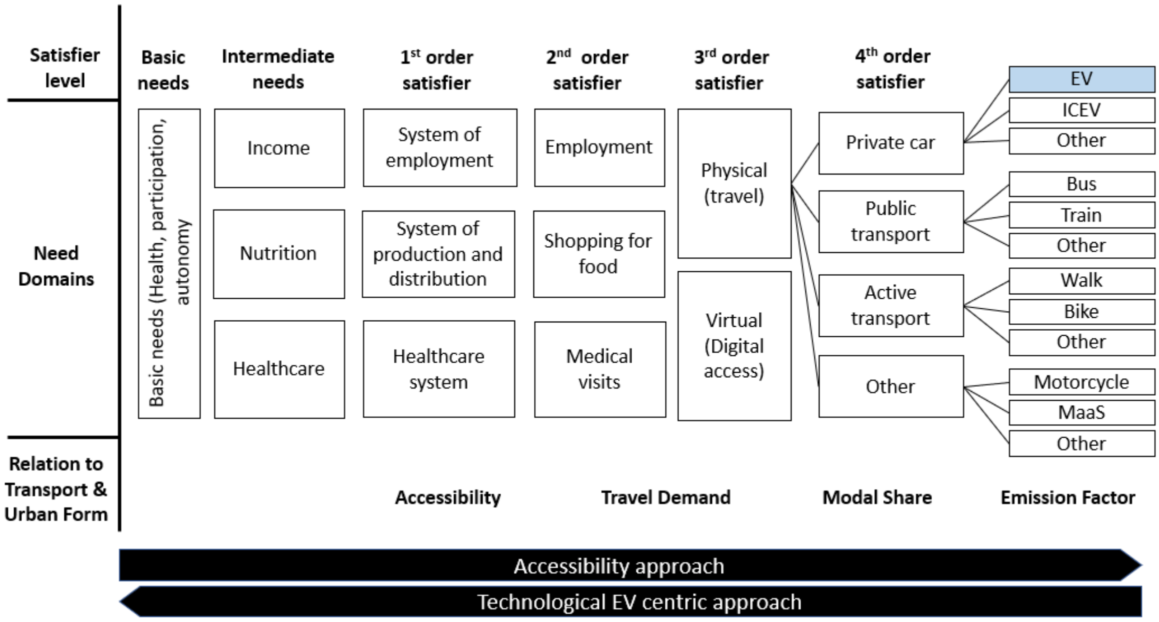

Figure 12. Adapted needs-satisfier chain adapted from Paper IV with additional transport system related aspects incorporated

3.2 Paper I results

3.2.1 Qualitative review results

Paper I provided both a qualitative assessment from the LCA literature review as well as quantitative results from the meta-analysis to understand the product level implications of EV use. Through qualitative assessment performed during the review and data collection process, three primary categorized sources of variation between studies were identified:

1. Methodological, goal, and scope differences between studies
2. Varying assumptions and contextual differences
3. Different levels of data availability and granularity of the data

Previous EV LCA reviews (Nordelöf et a. 2014; Hawkins et al. 2012) had identified the lack of clear goals disclosed in EV LCA studies, and, providing further depth, Paper I's review found differing life cycle phases and characterizing details within the life cycle phases across studies, illustrating not just varying or lack of goals, but the persistence of this issue within the scope setting process as well. In particular, noticeable differences in scopes were related to the inclusion of end of life and the requirement for battery replacement within the life cycle of an EV. The latter issue has a significant impact on the final life cycle emissions associated with an EV, and these issues together highlight the uncertainty within EV LCAs and the EV sector, in general, surrounding the EOL of EVs. Of additional importance highlighted within Paper I regarding this first category of sources of variation was the different approaches observed within life cycle phases between studies. Across the review, articles provided significantly different levels of detail regarding the approach taken within life cycle phases, and significant variations were found of what was included in them (for example the inclusion of road maintenance within the maintenance life cycle phase), which could potentially be an important source of variability in LCA results between studies.

The second identified category of sources of variation was the variation in assumptions and contextual differences between studies. In particular, the electricity source, production location (and associated location GHG electrical grid intensity), battery capacity, assumed vehicle lifetime, and energy efficiency were variables that saw significant variation between studies. Paper I provides a detailed overview of the observed differences between studies of each of these variables.

The last categorized source of variability identified between studies was the levels of data availability and granularity between studies. The lack of data availability in EV LCA studies was identified in Hawkins et al.'s (2012) review, and Paper I's review found a continuation of this issue in studies since the publication of Hawkin et al.'s review. While it is understood that LCA studies may contain some confidential information, the total lack of data availability makes reproducibility and use of LCI data near impossible. Other weaknesses in the disclosure of LCA data in the studies included the aggregation of emissions within studies, and this can be seen particularly in the aggregation of the battery pack emission data within the production emission life cycle phase, which then makes it infeasible to tease out the production emissions from the battery pack which would allow for relevant and important analyses surrounding battery pack environmental impacts.

3.2.2 Quantitative meta-analysis results

Following the qualitative results provided by the review in Paper I, a set of quantitative analyses were then performed. To reduce redundancy, this thesis guides the readers to the results section of Paper I to see the full array of quantitative results associated with the meta-analysis. This section does, however, discuss some of the interesting quantitative results derived in Paper I through the operationalisation of the meta-data, which provided a product level comparison of EVs vs ICEVs.

First, through the meta-data collected during the review process, a statistical data set was generated for each life cycle phase by vehicle type (EV, diesel ICEV, petrol ICEV). This resulting data set supported the common assumption that EVs have higher production emissions than comparable ICEVs, where the average production emissions per EV were estimated to be 64% and 77% higher than the compared petrol and diesel ICEV, respectively.

With this statistical data set prepared and using a consistent source for GHG intensities of European national electric grids which incorporated electricity trading, multiple GHG environmental breakeven calculations were then performed to provide EV versus ICEV product level comparisons. In these product level comparisons, it was determined that of the two comparators, diesel ICEVs were environmentally more competitive with EVs as compared to petrol ICEVs. Across Europe, where the lowest and highest GHG intensity electricity grids used could be attributed to Iceland and Latvia, respectively, it was found that in only in Cyprus, Poland, and Latvia, and only for a diesel comparator, the life cycle emissions of an EV were estimated to be higher than those of an ICEV over the full life cycle of the vehicle (assuming a lifetime of 183,894 km, the average amongst all studies reviewed). Paper I additionally provided "emission disparity" results, which estimate the difference in final life cycle emissions of an EV against the ICEV comparator in each country assessed. These calculations prove useful in understanding the resulting lifetime benefit (or cost) of using an EV versus an ICEV and, depending on the GHG intensity of the country's electricity grid ,whether this difference is significant or marginal.

As a sensitivity analysis, using the statistical dataset provided by the meta-analysis, a Monte Carlo simulation was performed as described in the methodology section, where the probability that an EV would lead to less life cycle emissions than the compared ICEV was mapped across the spectrum of electrical grid GHG emission intensities, shown in Figure 13.

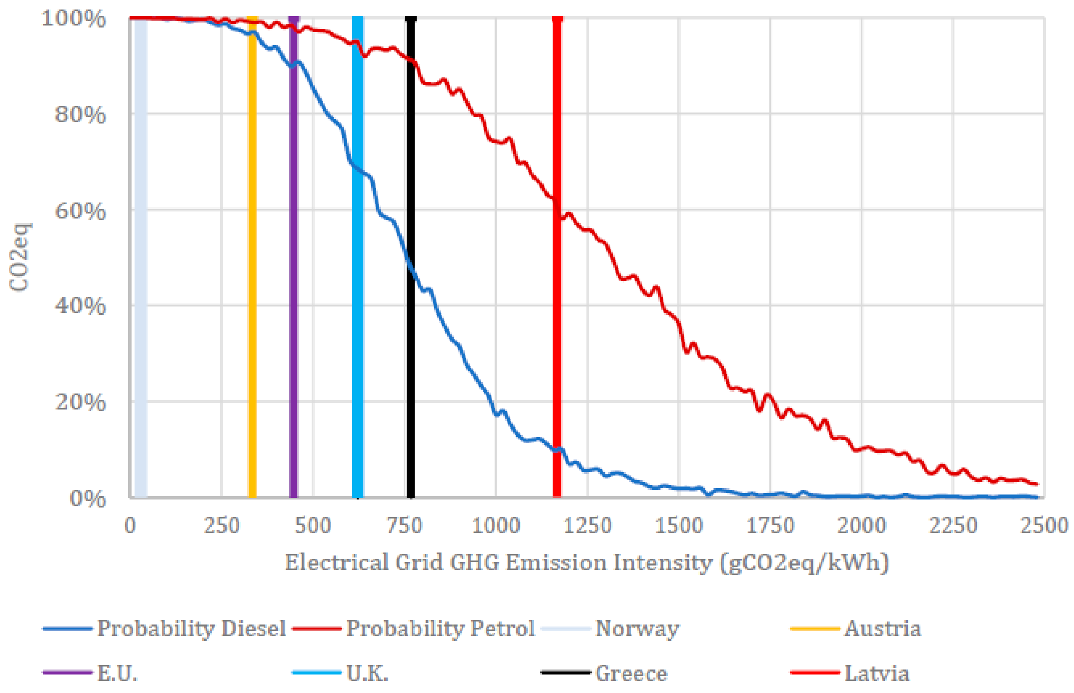

Figure 13. Monte Carlo simulation of the probability that EVs lead to lower life-cycle emissions than ICEVs for different electrical grid greenhouse gas (GHG) emission intensities. The blue line is compared to diesel and the red compared to petrol (Image and caption taken from Paper I)

The qualitative and quantitative results in Paper I assisted in providing the product-level perspective necessary to begin answering the research questions of this thesis, in which the GHG implications of EV use were estimated and an understanding behind the drivers of GHG impacts and contextual differences between studies was developed. With an understanding of the product level impacts, with a research goal of understanding EVs' role within urban transportation systems, this research then turned its sights towards urban level perspectives.

3.3 Paper II results

The first perspective of EV/technological versus behavioural development pathways is interesting because while Paper I was able to provide results that can characterize the impact of switching an EV out with an ICEV, private vehicles are not the only transportation alternatives that exist. Alternative transport modes can additionally serve transportation needs, and thus at an urban system level, the question extends beyond a simple replacement of ICEVs with EVs. Additionally, through the understanding of vehicle life cycle emissions at a product level and the importance of considering embedded emissions, both direct and indirect emissions were incorporated within the study. Exploring these implications, Paper II investigated this field of enquiry through the development pathway scenarios derived following the methodologies described in Section 2.2.

The full qualitative descriptions of each scenario developed in the SAS can be found in Paper II. For the purposes of this thesis, this section highlights the results from three of the six scenarios, namely: the technological change scenario (S3), which focused on EV integration; the urban structural change and lifestyle change scenario (S2), which focused on low and shared mobility; and the radical change scenario (S6), which incorporated both a rapid transition to EVs as well as a strong focus on shared and low mobility. In terms of annual total GHG emissions associated with both direct and indirect emissions, the S2 and S3 scenarios performed similarly, though more rapid decreases were seen in the S2 behavioural scenario due to lower fleet changeover requirements. However, through the decomposition, the reasons behind this result could be seen, and they were drastically different between the two scenarios. The S3 technological scenario with high levels of EV integration led to higher cumulative indirect GHG emissions than even the BAU scenario due to the higher embedded emissions associated with EVs, but offset this increase in indirect emissions with a large reduction in direct GHG emissions due to the high rates of vehicle electrification in a location with a highly decarbonized electric grid. Conversely, the S2 behavioural development scenario saw decreases in both direct emissions, through the greater use of public transport, active transport modes, and reduced travel demand, and indirect emissions through fleet size reductions. The S6 radical scenario took advantage of both technological and behavioural developments to lead to the greatest cumulative GHG reductions by nearly a factor of two as compared to the next best pathway in terms of decarbonization.

3.4 Paper III results

The second perspective of interest and oft-noted as a concern for the uptake of EVs is the impact of EVs on the grid, both at a city and distribution level (Milovanoff et al. 2020). Paper III thus performed a spatio-temporal analysis, estimating the additional peak load that EV integration would cause at these two granularity levels according to different policy scenarios which would lead to varying levels and rates of EV integration. The results of this work showed that in the worst-case scenario, uncontrolled home charging EVs would certainly add to the peak load at both spatial levels, with the maximum peak load at the grid level estimated to increase by 43–58%, 55–92%, and 67–114% across the different levels of EV integration caused by the policy scenarios. Additionally, using a specific substation as an example (using the substation which would receive the most disproportionately large amount of the load), the maximum peak load on that substation could potentially increase by as much as 29–39%, 47–76%, and 58–95%. These different rates of electrification could lead to different system costs at the distribution level, where Paper II estimated that the NPV of the system costs required to ensure reliability in the grid would double from the lowest integration rate as opposed to the highest integration rate scenario. Additionally, the greater electricity demand associated with these higher peak loads would require greater electricity supply and system capacity.

3.5 Paper IV results

With the product and urban level perspectives provided by the results of Papers I-III, EVs' role in improving the sustainability of an urban transportation system was investigated. These results were solely directional, however. While they may describe the movement towards a more sustainable state, lacking is the definition of a sustainable state itself. How would it be known if a sustainable state had been achieved? And what does it mean for an urban transportation system to be “intergenerationally sustainable"? These questions were the second research objective of this thesis and the results of Paper IV took the first steps towards answering them.

Figures 14 and 15 were provided in Paper IV, but are worth re-examining to provide context for a discussion here and within the following sections. Figure 14 displays the EC which was established with the domains assessed to be relevant to the transportation sector defined. With the knowledge gained from the EV LCA literature review, studies of urban level impacts from the transportation sector, and further literature review, Paper IV attempted to map the sector-relevant environmental impacts to different PBs and their spatial impacts (with acknowledgement of the interrelated aspects of the PBs). It can be seen that the direct and indirect emissions related to transport were split, and their impacts were associated with output-based thresholds. Additional domains defined by the PBs included land system changes, biosphere integrity, and fresh water use, which were respectively related to transport systems issues such as land-use change (i.e. road construction), biodiversity impacts (i.e. wildlife collisions, fragmentation), and impacts to freshwater (impermeability).

By defining this ceiling, the logic is that from a consumption perspective, as an example, the sum of the direct and indirect emissions from transport should remain below certain per capita value (or national total) such that if everyone abided by such a system that humanity would remain within the gross carrying capacity of Earth's Systems, in this example, that being climate change and the ppm threshold of the climate change PB (Röckstom et al. 2009).

Driver	Transport demand, energy efficiency, modal share	Car ownership, fleet size, transport infrastructure	Urban density, land use, road network	Urban density, land use, road network	Impermeability, embedded water use in transport goods and infrastructure
Pressure defined by	Direct Emissions related to transport (Tank-to-Wheel Emissions)	Indirect Emissions related to transport (Well-to-Tank emissions, Production emissions, disposal emissions, embedded emissions in infrastructure)	Land use change/impact caused by transport system	Impact of transport system on biodiversity	Impact of transport system of fresh water system

Domain/State Domains	Output Based Thresholds [Climate change (global), Biogeochemical flows (local), Ocean acidification (global), Atmospheric aerosol loading (global), Stratospheric ozone depletion (global), Air pollution (local)]	Land-system change (local)	Biosphere integrity (local)	Fresh Water Use (local)	Ecological Ceiling

Figure 14. Framework for developing indicators of the environmental ceiling in the sustainable consumption corridor for mobility. While presented in the figure as distinct, it is understood that overlaps between impacts across the domains exist

In addition to taking a first step in defining a mobility sector-focused EC, Paper IV additionally set out to establish the SF for the mobility sector. Figure 15 shows the results of this work, where using a eudaimonic perspective/sufficiency approach to SF development and relevant aspects of transport poverty, the mobility-focused SF was constructed, with accessibility poverty, mobility poverty, and exposure to transport externalities acting as the primary SF domains.

Mobility-focused Social Foundation

Domain	**Accessibility**		**Mobility**		**Exposure to transport externalities**	**SOCIAL FLOOR**
Definition	Ability to reach essential services and opportunities within means, i.e., at reasonable time, ease, cost		Ability to travel via having access to, usually motorised, travel modes, related services or infrastructures within means, i.e., at reasonable time, ease, cost		The outcomes of disproportionate exposures to the negative effects of the transport system	
Sub-domains	Systemic accessibility: Essential services and opportunities being accessible	Individual accessibility: Having access to essential services and opportunities	Access to mobility: The ability to travel certain amount (e.g. in terms of travelled distances)	Access to travel with specific modes of transport, (e.g., public transport, bicycle, shared car, private car)	Road traffic casualties, chronic diseases and deaths from traffic related air and noise pollution	
Order of need satisfiers (Mattioli 2016, Gough 2017)	1st (intermediate needs - systemic)	2nd (intermediate needs - individual)	3rd (travel)	4th (travel modes)	Physical health (basic need), non-hazardous physical environment (intermediate need)	
Poverty and social exclusion approach (Lucas et al. 2016)	Accessibility poverty, i.e., the difficulty of reaching certain key activities at reasonable time, ease and cost		Mobility poverty, i.e., the lack of : (usually motorised) transport; Transport affordability, i.e, inability to meet the cost of transport		Exposure to transport externalities, disproportionate negative exposures to the transport system itself	

Figure 15. Framework for developing indicators of the social foundation in sustainable consumption corridor for mobility. While presented in the figure as distinct, accessibility and mobility indicators overlap (Lucas, et al. 2016).

Accessibility poverty is associated with the lack of ability to reach essential services and opportunities with reasonable time, cost, and ease. Accessibility was suggested as the first domain following a needs-satisfier chain approach (based on Mattioli 2016; Gough 2017), where before addressing the mobility system, which in itself does not address any basic (such as health or social participation) or intermediary needs (such as income, nutrition, healthcare) and can rather be considered the means to achieve these primary needs, it was considered that access to these needs be prioritized first. This means that before considering how to maximize the potential for movement, which has the potential to escalate need satisfiers, first how to enhance the ability to access these needs-satisfying goods and services should be considered (Handy, et al. 2002). This serving of higher-level need satisfiers has directly and indirectly been a growing perspective in mobility and urban planning lines of thinking (Mattioli 2016, Lucas, et al. 2016; Simon 2016). With accessibility addressed, the mobility system can then be examined, where mobility poverty could then be described as the lack of access to sufficient mobility infrastructure, services, or travel modes with reasonable time, cost, and ease which would allow one to access available basic services. Separate (though still with some overlap) from these two interrelated domains is the final domain of the externalities associated with the transport sector, such as chronic disease and illness caused by air pollution, traffic casualties, and noise pollution which can impact a population's ability to live a dignified, healthy, and safe life.

Paper IV then associated an established indicator set (Sdoukopoulos et al. 2019) to these domains, the results of which can be seen in greater detail in the article. These associated indicators were connected to the domains of the ECs, SFs, or both, and their strength of relation to the domain (direct or indirect) and sustainable direction (i.e. determination of if an increase or decrease of the indicator would indicate movement towards a more sustainable direction) were assessed. This indicator association exercise provided the basis for discussion surrounding SUM indicators, where a subset of indicators was identified, such as car ownership rates, which had conflicting environmental and social sustainable directions. For instance, in the car ownership example, environmentally, reduced car ownership would reduce emissions associated with the production of vehicles and fewer cars on the road, however, socially, in some studies car ownership is seen as a factor that should be increased to improve mobility. These results highlight the importance of taking an integrated environmental and social perspective when developing indicators as well as speak to the need for developing thresholds and SCC relevant indicators as a novel way to measure sustainability in mobility systems.

4 Discussion

This discussion first addresses how the thesis answered the research questions. Subsequently, a broader interpretation of the integrated results is provided, highlighting the importance of urban perspectives and the value of contexts when discussing EVs from an environmental, socio-political, geographical, and socio-technical perspective. These interpretations are then synthesized before reviewing some of the barriers related to the different development pathways discussed in the thesis and evaluating the validity and reliability of the study. Lastly, the future research identified by the study and some concluding remarks are provided.

4.1 Addressing the research questions

Electric vehicles' perceived global role as a key enabling technology for the decarbonization of the transportation sector is continuously expanding. This political focus alongside technological developments have led to a rapid increase in global EV fleet size where, as of April 2021, twenty countries had already announced electrification targets and/or ICEV bans (IEA 2021). With these policies established to decrease GHG emissions and other environmental impacts (such as local air pollution), the importance of understanding the environmental implications of their uptake is paramount, particularly as public debate often leads to questions about their environmental mitigation potential (Linda 2019; Ortar and Ryghaug 2019). This thesis thus investigated the implications surrounding EV uptake with three primary research questions:

> **RQ1:** *What is the direct and indirect decarbonization potential of EVs at the product level?*
>
> **RQ2:** *What is the direct and indirect decarbonization potential of EVs at the urban level (informed by a product-level life cycle perspective), and how will their integration potentially affect the electrical grid due to additional peak load?*
>
> **RQ3:** *How can an intergenerationally sustainable 'safe and just' urban mobility sector be characterized?*

This thesis addressed these research questions through a multi-scale approach in which first EVs were assessed at the product level through a review and meta-analysis of comparative EV/ICEV LCA studies. The results from this first level showed that throughout Europe in almost all grid contexts EVs would provide climate change mitigation benefits as compared to petrol and diesel vehicles, though the extent of the mitigation potential is highly determined by the grid intensity, particularly when compared to diesel vehicles, which were found to have lower life cycle impacts than their comparable petrol counterparts.

Answering RQ2, at the urban level, through the scenario analysis performed in Paper II, for the Reykjavik case study (which represents a near best-case scenario for EV implementation in terms of the provision of low-carbon electricity), the results showed that with uncontrolled fleet growth, an EV techno-centric approach would result in a similar if not worse GHG scenario than a behavioural development pathway focused on demand-side solutions. Additionally, more rapid integration rates of EVs without fleet size control will also likely lead to greater grid impacts and require sooner preventative action (and reactive, if not appropriately addressed) by electrical grid operators. These results provide the answer to RQ2 in which it can be said that EVs certainly have life cycle GHG mitigation potential, but primarily at the product level. When considered in the urban context, answering RQ2, where public transport and active modes could potentially act as substitutes, their benefits are less obvious when considering direct and indirect emissions. The same can be said when it comes to potential impacts on the electricity grid due to added peak load. These results reflect other studies, which have shown that EVs alone may not help countries and regions achieve set climate targets (Sager et al. 2011; Shafiei et al. 2019; Milvanoff et al. 2021).

Answering RQ3 of how an intergenerationally sustainable urban mobility sector could be characterized, Paper IV took the first step towards this goal, characterizing both an EC and an SF for an urban mobility-focused SCC. The integrated results showed the importance of placing the urban mobility sector within the context of an SCC. For example, as shown Figure 11, the importance of including environmental thresholds in the development of decarbonization pathways can be seen, where, when considering the direct and indirect impacts of the scenarios, the challenge of remaining within the SCC becomes increasingly obvious -- especially when considering the need to incorporate other consumption sectors into these boundaries. From a social perspective, by taking a needs-based approach, this additionally helped provide an important perspective for transport development, where, when mapping the needs-satisfier chain, it was made clear that an EV-centric approach addresses the ‘means’ (to the end) as opposed to first addressing the ‘end’ (basic need and accessibility to its satisfier) itself.

4.2 Interpretation

In answering and interpreting the answers to the research questions, it was determined that first some elucidation surrounding urban form and accessibility perspectives and the importance of context within the interpretation of the results were needed. While a plethora of additional perspectives could be added to the interpretation of the results, the inclusion of these perspectives was deemed relevant, firstly, given the importance of the accessibility approach in both the overarching results of the thesis as well as the surrounding discussion. Secondly, the same could be said of the importance of context within the results, where, for example, the Reykjavik case studies performed at the urban level in this thesis represent a context of a sprawled urban setting with a high GDP per capita, supportive EV policies, and a highly decarbonized grid, amongst other defining features. Thus, when interpreting the results this context becomes largely important, as will be discussed in the following subsections. With these added perspectives, the final interpretation is provided, followed by barriers to some of the different socio-technical development approaches discussed in this work to provide a further understanding of the limitations to some of the approaches discussed.

4.2.1 Urban form and accessibility perspectives

Urban populations are expected to grow both in gross terms as well as in terms of the percentage of the human populace living in an urban context. In tandem with this growth, urban land area is expected to double in just the next 20 years (Rode et al 2014). In response to this growth, many international initiatives have pushed densification as a key promoter of greater urban sustainability and economic development (World Bank 2009), with the three benefits identified being reduced car travel and associated impacts, more efficient urban land and infrastructure use, and more inclusive, vibrant communities (Turok 2011). However, increasingly research surrounding city densification is coming to show that density for density's sake does not seem to be the right answer (Simon 2016). On the one hand, it has been largely shown that increased density leads to reduced car ownership, and lower rates of car ownership can be connected to reduced transport emissions and associated energy use (Ki-moon 2013; Newman and Kenworthy 2015). Greater density additionally can be connected to the reduced road and other infrastructure requirements per capita (Rode et al. 2014), which can have significant impacts (Chester and Horvath 2009). However, other studies have identified that increased density does not always reduce car travel, and instead can increase traffic-related issues such as congestion, parking-related issues, and accidents (Simon 2016). Socially, the outcome of densification appears to be a mixed bag of results. While densification has certainly produced beneficial economic outcomes of agglomerated populations leading to greater employment opportunities, productivity, and efficiency, it has also been shown to lead to increased cost of living and decreased access to green spaces, though these results almost always require contextualization (Dempsey et al. 2012). Further, there is the potential for densification and reduced car ownership to correlate with increased consumption and consumption changes (Heinonen et al. 2013; Ottelin 2017), such as higher frequency of flights (Ottelin 2014; Czepkiewicz et al. 2019), which could lead to rebound effects greater than the offset emissions (where rebound effects will be discussed in greater detail in Section 4.3.2). In Section 4.2.2, the contextual importance of both urban and urban mobility contexts will be discussed in greater detail.

Recognizing the shortcomings of a sole density approach, there have been growing proponents of an accessibility approach, in which, rather than only using density indicators to measure the efficiency and impact on travel within a city, more holistic social indicators be included to incorporate factors such as equity, diversity, connectivity, affordability, and intensity. Thus, rather than just focusing on the development of dense cities, researchers, urban planners, and governments should be focusing on the development of accessible cities, which enhance the ability of the city's inhabitants to satisfy their needs through participation in necessary or desired activities (Simon 2016). Advocates for accessible cities have thus called for cities to enhance accessibility through the thoughtful measurement and recognition of access to public spaces, public/active transport, employment, recreation, community, affordable housing and transport, as well as the proper power and justice institutions to support these goals, to complement the focus on densification (Iacono et al 2010; Tahmasb et al. 2019).

The accessibility approach illustrated by Figure 12 acknowledges an urban transportation system's role as a means to an end rather than an end in itself. An urban mobility system is embedded within the urban form of a city to serve the mobility needs of the city's constituents, and how they satisfy those needs is inexorably interrelated to the city and its development. It would thus be remiss to discuss EVs and the sustainable transformation of the mobility sector without placing it with the larger dialogue of sustainable cities and urban development, particularly since this larger dialogue has been taking a similar direction in the context of sustainable development.

The goal of an accessibility approach such as the one shown in Figure 12, is to first most effectively and sufficiently meet the needs of all the city's populace, where it is recognized that the urban mobility system is but a subsystem (though an important one), of an urban system in general. Therefore, urban planning and urban mobility system researchers can set their sights towards the development of more accessible cities, taking sufficiency and integrated environmental perspectives into account, moving the co-dependent systems into a 'safe and just' space. Through this multi-layered perspective, this thesis suggests that more holistic development pathways can be envisioned, where EVs play a role within the larger vision instead of that of a "silver bullet" solution. What role EVs should play in different urban settings, however, requires contextualization.

4.2.2 Contextual importance

Cities and their interrelated mobility systems have each historically and spatially developed in unique pathways in order to provide their inhabitants access to employment, information, goods, and services. How effective a city is in providing its inhabitants access to these basic goods and services has been shown to have a direct economic benefit (in terms of GDP per capita and productivity) through economies of scale, agglomeration, and network effects (Rode et al. 2014). In the 1970's and 1980's, a subset of urban researchers were attempting to define an optimal size for all cities in which the marginal benefits and marginal costs of city size would come into equilibrium (Richardson, 1972). However, future research would come to recognize the futility of defining a single optimum city size, acknowledging that rather the far more likely solution is that there are infinitely many optimal city sizes depending on the city in question's context (Carmagni et al. 2013). Thus, how cities provide for their citizens vastly differs between cities, where the urban form and characteristics of the city and its inhabitants, as well as their interrelated environmental impacts, are connected to factors including population density, urban metabolism, electrical grid emission intensity, income levels, mobility culture, industrial activity, and urban form, which vary widely globally. In their goal to decarbonize, cities need to address these contextual differences and consider them when contemplating development pathways (Kennedy et al. 2014). Through the interrelated aspects of urban form and urban mobility systems, the latter must similarly come to terms with these contexts when considering sustainable development pathways.

The importance of these factors will now be investigated in the context of EVs, starting with the interrelated roles of population density and the car orientation of cities. There is a well-established link between urban form and energy use from transport (and associated emissions), largely due to the use of private motorized vehicles. The IPCC has suggested that through the long and medium-term, more compact cities which support greater use of public transportation and active transport modes could lead to GHG reduction between 20-50% compared to 2010 levels, highlighting the benefits of densification in terms of meeting decarbonization goals (IPCC 2014b). Less dense cities tend to be more car-oriented, where more dense cities tend to see higher rates of public/active transport mode use. Concerning development pathways, this should also extend to future states, as described in the scenarios developed in Paper II, where the development towards a more compact city would likely lead to increased rates of public transport/active transport modes and vice versa for a less dense city, where travel modes would increasingly skew towards private motorised transport.

In the context of EVs, following the results from Paper II and III this would likely mean smaller car fleet sizes and reduced energy use from EV integration. Conversely, less dense cities would instead likely have larger car fleets which would require greater vehicle turnover (and associated EV turnover according to EV penetration rates), leading to greater embedded emissions and material use in general, and increasingly so with higher EV penetration rates.

These conclusions then expand into the greater conversation around car culture and the reflection of this cultures in the built environment of cities, where lock-in due to infrastructure and resistance to car-dominated paradigms may occur. Urban sprawl and the prevalence of private vehicle-oriented infrastructure can be largely attributed to the introduction of vehicles and city design around their use. Thus, there have been studies questioning the integration of EVs, with the fear that this integration without considerations of fleet size or urban form will cause a continuation of the car-dominated paradigm and run counter to the goal of sustainable urban development focusing on accessibility and density (Driscol et al. 2012; Henderson 2020). Other studies have additionally recognized car culture as a barrier to sustainable urban development, where the historic infrastructure and social value of car ownership (perceived through status and personal choice) can make the implementation of densification and alternative transport mode supporting policies difficult (Fabio 2018; Moody et al. 2021). Lastly, the changeover costs of the existing infrastructure for low-density, car-oriented and/or sparsely populated areas which have already developed through urban sprawl can present significant barriers in the forms of prohibitive costs to the implementation of public transit and densification strategies (Rode et al. 2014). Spatial discussions can additionally extend to use cases between urban, suburban, and rural, where studies usually take urban and suburban perspectives and the rural use case is usually left as a secondary discussion (Kester et al. 2020; Newman et al. 2014). Summarizing these points, the role EVs have to play in addressing sustainable urban mobility development additionally needs to consider the car orientation and car culture of the area under consideration, recognizing the benefits and limits of EV integration.

In the consideration of benefits, the next most obvious factor to consider is the electrical grid and its carbon intensity for the region of study. Paper I highlighted the importance of electrical grid intensities and Figure 13 illustrated the electrical grid intensities in which EVs begin to clearly have an environmental advantage as compared to petrol and diesel vehicles. Paper III then provided the potential impact EVs could have on a city's electrical grid. Extrapolating from this, it is obvious that in gross terms without charging control, EV integration will additionally lead to increased electricity use and peak demand which will then require greater electricity system capacity. How countries then meet that capacity and the ability for renewables to meet this additional need on top of the area's consumption from other sources needs to be factored in when considering EV integration. Kennedy et al. (2014) provided a useful chart depicting a 2-axis plot of population density and electrical grid GHG intensity, highlighting where EVs serve a most applicable role of decarbonization (in their work identified as cities with grid GHG intensities less than 600 $gCO_2eq./kWh$ and population densities less than 6,000 people per km^2, (where the GHG intensity was in line with the findings from Paper I) as compared to other solutions such as Bus Rapid Transit systems[15]. This assessment was done considering energy use from houses well and thus lacked the granularity needed for in-depth mobility system guidance. Such breakdowns are

[15] With the 2020 Reykjavik population estimated as 224,709 (City of Reykjavik 2020) and an estimated area of 273 km2 (EDS 2004), this would make the population density of Reykjavik approximately 823 people per km^2.

useful in developing the conclusions of this thesis, where it is suggested that the implementation of EVs needs to be contextual.

The last contextual factors considered within this thesis are the political-economic factors of different cities globally. Many of the previous discussions have been based on evidence from WEIRD (western, educated, industrialized, rich and democratic) countries. However, with most of the 21st-century population growth likely to occur in developing countries, it is worth expanding on the contextual relevance of the Global South in the discussion of sustainable cities and sustainable urban mobility and understanding to what extent the findings of this study are transferable. First and foremost, it is worth highlighting the difficulty in assessing urban and urban mobility systems in developing countries due to lacking data and largely differing and at times volatile economic, social, and political systems (Bouttueli and Aguilera 2018). Despite these issues, it can be seen that along with rapidly growing populations, the rate of urbanization in developing countries is also rapidly increasing, and this movement towards urban centres can potentially lead to crowding and, while dense, adverse social outcomes may occur through the development of 'squatments' and 'slums' where access to basic needs and services are limited rather than enhanced, countering the benefits touted by densification advocates (Huchzermeyer 2011; Simon 2011). From a mobility system perspective, historically it can be seen that developing countries have had lower rates of motorization and higher use of public, active, and informal transport modes of different forms (Bouttueil and Aguilera 2018). More recently though, as developed countries have approached what has been termed peak car for a variety of suggested reasons (lifestyle changes, anticar policies, digitalization), developing countries, especially China, have seen rapid rises in rapid motorization, and coupled environmental impacts, approaching that of their developed country counterparts as they close the economic gap between the two (Kutzbach 2009; Bouttueil and Aguilera 2018, Steffen et al. 2015). This change of incumbent transport modes to motorization and associated urban form changes (or lack of supporting changes, leading to increased congestion) may additionally cause social inequities, particularly with the historic infrastructure often developed in favour of the ruling and elite classes. If access to transport services is disparate between classes, income inequality can be exacerbated due to insufficient and unequal urban transport accessibility (Simon 2016). Further enhancing these inequalities, car ownership has been linked to household income (Whelan 2007; Woldeamanuel et al. 2009), and the inability to afford a car can then be a limiting factor of accessibility as well, where in disadvantaged communities there have been signs of forced car ownership to gain access to opportunities (Boisjoly et al. 2021). While these issues are being related to the Global South, the are also very relevant to some of the income and other inequality conditions found in OECD countries such as the U.K., Germany (Mattioli et al. 2017), the U.S. (Curl et al. 2018), and Iceland (Heinonen et al. 2021).

EV studies additionally have often focused on developed countries and China, where they see the highest fleet sizes and penetration rates, thus also lacking a Global South perspective (Rajper and Albrecht 2020). However, given the increasing urbanization and motorization rates occurring in developing countries, it is equally important to understand the role of EVs in both contexts. Indeed, the context of EV expansion in developing countries has additional factors to consider, such as differing grid contexts and affordability concerns (though as will be discussed in Barriers to EV integration section, affordability concerns persist in both developing and developed countries). As developing countries, and particularly those which are rapidly developing, close the income gap between themselves and developed nations, without evidence of economic-environmental impact decoupling occurring, so too have their GHG emissions and environmental impacts developed. As of 2018, OECD and non-OECD countries saw 22% and 47% use of coal and 27% and 21% use of renewables, respectively (IEA 2021). This greater use of coal by developing countries highlights the importance of understanding the electrical grid context of EV use, particularly as electrical capacity will need to continue to meet the rapidly growing electrical demand seen in developing countries (as opposed to the stagnating demand seen in OECD countries) (IEA 2021). Except for China, however, EVs have seen very little penetration or rising interest in developing countries (IEA 2021), though Rajper and Albecht (2020) do discuss the importance of two-wheeled electric vehicles in developing countries. While the barriers to EV uptake, in general, can be attributed to multiple technological, infrastructural, political, and financial causes (Liao et al. 2015), particularly in developing countries, at a state level, the political ability to provide subsidies and invest in infrastructure, and at a household level, the affordability of purchasing and operating, can be particularly limiting (Rajper and Albecht 2020). In conclusion, when considering the integration of EVs, the political economy and grid infrastructure of the region should also be contextualized to understand the environmental, economic, and political feasibility.

4.2.3 Synthesis

All the different factors just discussed can create different path dependencies and development patterns. Following this line of thinking, this thesis suggests that with the interrelated role of urban form and transportation systems, when it comes to decarbonization/sustainable development pathways, there is no optimal development pathway. Rather, it holds that, using the SCC as a framework for the development towards a sustainable urban mobility system, a unique context-informed pathway should be developed according to the conditions of the urban area. Through such a contextual development with a focus on accessibility and awareness of ecological ceilings, the pitfalls of EV integration could be avoided and their benefits maximized.

If one were to think about the adapted Kaya identities in Figure 7, one could first ask, taking accessibility into account, if there is demand generated for this activity and if the city provides the means for it such that each citizen can live a good life. Once established, one can then ask, how can one take part in this activity? Can they attend digitally, or do they need to travel? If they do need travel, urban planners and policy makers could then look at the different variables. What type of push and pull policies and urban form changes could be implemented to affect these variables? What is the extent of the change that these policies could make? And which would have the greatest effect? The effect of this thinking is similar to that illustrated in Figure 16, where this thesis has imagined these questions in the form of a lever panel in which the current positioning of each variable is relevant to the current conditions of the specific variable in the urban centre's current state and the ability to move each lever is subject to each city's contextual ability to change this variable according to technology, culture, economic ability, geography, etc. Thus, with this mental framework, city planners could consider different development pathways, and researchers and modellers could assist in determining the potential costs and benefits (environmental, social, and economic) of each approach, and use the SCC framework for guidance towards a 'safe and just' space for the urban mobility sector.

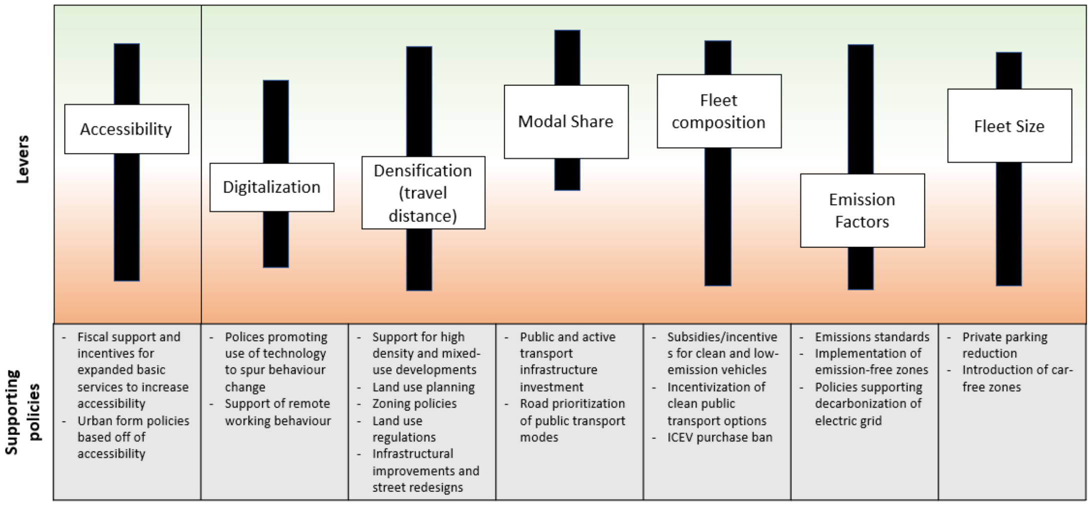

Figure 16. Illustration of mental schema for interpreting an urban area's current urban system and the levers (adapted from the ASI approach and Kaya identity for transport) to develop more sustainably (or less so, i.e. towards a less efficient sprawl), where the black boxes represent the hypothetical maximum or minimum ability for policies (or lack of them) to move the specified factor in a specific direction

Synthesizing this perspective and the accessibility approach direction taken in Figure 12, in the multi-scale approach about EVs' role in decarbonizing the urban mobility sector, its potential additional effects, and the context of global intergenerational sustainability, it is the claim of this thesis that EVs certainly can act to reduce GHG emissions as compared to ICEVs in the right contexts, but that this substitutional view is limiting. Rather, why mobility is needed should be first be examined, where determining how to increase the accessibility to goods and services that provide the means for a good life should be prioritized. Then, the mobility sector can be assessed, and in this view, EVs have a role to play, but how large of a role is contextually dependent and should incorporate both direct and indirect environmental impact within the lens of the planetary boundaries and the social foundation where all citizens should have the right to live a good and dignified life as well as the access to achieve this.

This conclusion and its ramifications are therefore a relevant response to the current dominating international narrative discussed in the introduction: while just recently the importance of ASI strategies have been noted by international works and initiatives such as the IEA and EU, an unbalanced focus is still placed on supply-side, technological, and often EV-centric approaches, which has also been seen at the urban-level through urban mobility-related climate policy making. Furthermore, these initiatives rarely discuss the context and methods in which ASI strategies can and should be implemented at the urban level, where a suite of solutions are discussed, but it is rarely discussed where and when they would be appropriate to introduce. Additionally, the idea of connecting these developments to intergenerational global sustainability defined by a 'safe and just' space is part of a nascent field of research and policy work.

This research can thus hopefully provide a timely perspective for urban transport researchers, urban level initiatives and planners, and regional/national policy makers towards a more nuanced approach to sustainable urban mobility development. By avoiding an overemphasized approach based on a single solution (in this case EVs), the approach suggested in this thesis can hopefully avoid O'Neill's et al.'s (2018) fear of Raworth's doughnut economy becoming an unachievable vanishingly thin ring in which social provisioning systems are not capable of servicing our needs whilst maintaining earth systems' stability due to a lack of consideration of embedded impacts and contextual factors. Rather, this work hopes to provide a basis for the de-escalation of need satisfiers in the urban transport sector. Through the SCC perspective put forward by Paper IV, social provisioning systems can be characterized and assessed, and developmental pathways informed by the urban centre in question's context developed, such that pathways can be derived where the social provisioning system can provide as great of a service level as possible whilst decreasing material and energy intensity. Such an approach could hopefully inform future studies and initiatives, where, for example, climate policies and particularly sectorally focused policies such as SUMPs, could be linked to social outcomes and to EC thresholds, which have been noted as missing (Lamb et al. 2020; O'Neill et al. 2018). This would work to breach the intellectual dead-end identified by Grossman et al. (2021) in which explicit interlinkages between social and ecological transport research are often missing. This work could thus provide a basis for further implementation of such doughnut economy approaches now being seen in cities such as Amsterdam and Barcelona at a more granular sectoral level, which could allow for improved management and targeted policy setting.

4.2.4 Barriers

Within this greater interpretation of the results of the study, it would be remiss to not consider the barriers in implementing the variety of urban form, urban mobility, and technological transformations discussed in this work. As illustrated in the mental level panel diagram shown in Figure 16, the ability to move a variable in a certain direction is subject to the existing barriers for such a developmental change. This becomes relevant to this thesis, because to assume that a movement in one direction is as straightforward as development in another direction can be misleading. Barriers may exist for a variety of cultural, infrastructural, political, geographic, technological, and economic reasons, amongst others. Thus, three primary developmental barriers to some of the concepts discussed in this thesis are reviewed, with an understanding that this is not an exhaustive list but rather those most relevant to the thesis.

Barriers to EV integration

Given this paper's primary focus on EVs, barriers to EV integration will be the first topic considered. These barriers can be technological, political, social, infrastructure-related, and economic. Examples of each can be seen in the expanded list in Table 2. In an evolving market such as EVs, the impact of these barriers in different regions and contexts make it difficult to predict the rate and potential of EV integration. For example, technological developments could lead to significant range increases and reduced battery costs, which could likely lead to more rapid rates of integration than would occur without these developments. Additionally, as climate concerns continue to grow, the urgency felt by governments to support EV developments could continue to increase, leading to greater subsidies and support for infrastructure. Considering developments (or non-developments) and their implications, it is important to understand the existence of these barriers when modelling the impact and potential of EV uptake.

Table 2. List of barriers to EV integration by barrier category (adapted from Adhikari et al. 2020; Berkeley et al. 2018)

Barrier category	Barriers
Technical Barriers	Range-related concerns
	Lack of charging infrastructure
	Lack of evidence from a new technology
	Availability of EV model options
	Limited or uncertain battery lifetime
	Charging time
Political Barriers	Government financial and policy support
	EV education awareness
Social Barriers	Lack of EV general knowledge
	Lack of environmental knowledge
	Lack of EV product knowledge
	Aesthetics and social perceptions
Infrastructure Barriers	Charging infrastructure,
	Home-charging housing related infrastructure barriers (i.e. apartments vs. single homes)
	Repair/maintenance expertise
	Supporting domestic industry
	Electrical grid and capacity related concerns
Economic Barriers	Purchase price
	Battery replacement
	Charging costs
	Resale value concerns
	Income levels relative to transportation costs (and EV costs)

Barriers to densification/accessibility

While the World Bank and other international institutions have hailed densification as a key sustainability approach to urban development (Simon 2016), barriers and challenges associated with densification/accessibility approaches have been identified, as displayed in Table 3. Highlighting some of the key barriers, while there are sustainability interests in limiting sprawl and reducing car dependency, as discussed in Section 4.2.2, there exist certain social desires for suburban lifestyles and car culture mentalities that can challenge these developments. Additionally, there are business interests in maintaining the status quo, where automotive, construction, and real estate developers (which often represent powerful actors) have proven resistant to change (Rode et al. 2014). This further relates to economic challenges surrounding decades of sunk-in costs of developing suburbanized car-centric cities which would require significant urban redevelopment to densify. Mattioli et al. (2020) further provide a systematic overview of the dominant political-economic influences on car dependence and the transport sector which make movement towards less car-oriented societies difficult. They suggest that the political-economic, industrial, and cultural structures identified by them which relate to the factors discussed above are part of a system of feedback loops which have led to the current regime of car dependence and carbon lock-in. Furthermore, fragmented governance, siloed governance, and lack of linkages between urban and national transport and climate policies can create challenges associated with management and oversight towards more densified development.

Table 3. List of barriers to densification by barrier category (adapted from Hernández-Palacio 2018; UN Habitat 2019; Mattioli et al. 2020)

Barrier category	***Barriers***
Environmental Barriers	Loss of green space
	Potential loss of local environmental quality due to decreased access of natural lighting and ventilation
	Intensification of local environmental issues such noise and pollution
	Potential reduction of local environmental services provided by nearby green areas
Social Barriers	Population growth (or shrink)
	Potential decline in the quantity and quality of children and elderly friendly spaces
	Preferences for suburban lifestyles and car ownership
	Increased perception of social tensions and conflicts
	Car dependence
	Public transport provisioning (or lack of)
Institutional Barriers	Conflicting interests of industry, public planning agencies, and private urban developers
	Administrative fragmentation
	Scarcity of resources (technical, economic, human)
	Legal frameworks and procedural traditions
Economic Barriers	Pre-existence of large sprawled peripheries and massive sunk investments in their infrastructure (both housing and transportation infrastructure)
	Complex and costly urban renewal and brownfields redevelopment processes
	Scarcity of space to the location of large business dependent on parking facilities to operate
	Decrease in affordable housing

Barriers to implementation of ecological ceilings

The previous barriers and challenges discussed all represent obstacles to making directional movements towards sustainable development. Measuring and implementing policies that define and establish intergenerationally sustainable thresholds, however, presents additional challenges. Living a 'safe and just' life requires living within the Earth's carrying capacity as described by the PBs, but humanity seems ill-suited to meet this challenge. In Kallis et al.'s (2018) review of degrowth literature, it was acknowledged that the abandonment of economic growth as a key political agenda seems "impossible". The current capitalist socio-economic system does not leave space for progress without growth, but the current trajectory that we are on as shown by the Great Acceleration graphs and our current and impending transgressions of the PBs highlights the limits to this growth. Ecological economists have argued that GDP, resource use, and environmental impacts cannot be absolutely decoupled (Kallis 2018; Hickel and Kallis 2020; Wiedenhofer et al. 2020; Haberl et al. 2020).

Some may argue that efficiency of production can be done to avoid this, and while some relative decoupling has occurred, focusing only on increased efficiency does not consider scale, which is propagated by increasing global population, income, and even greater consumption due to the increased efficiency (Daly 1977; Blake 2014). For example, even when the Covid-19 outbreak forced humanity to restrict its movement and provision of services, emissions only dropped by ~6% in 2020 (Tollefson 2021). Thus, it appears that as the current dominating neoliberal agenda continues, the impacts of the prevailing global system seem likely to continue without significant intervention.

The most recent publication of Working Group I from the IPCC's Sixth Assessment Report has shown that without additional climate policies, even if all the NDC's from the Paris Agreement are met, 1.5-degree warming is still likely to occur by 2050. And the only scenarios which would not hit 1.5-degree warming would require significant removals of GHGs by the end of the century using yet unproven technologies (Keyßer and Lenzen 2021). Keyßer and Lenzen (2021) have noted, however, the IPCC's assumption of continued GDP growth in all scenarios without considering degrowth scenarios. Degrowth is a concept that runs counter to the current socio-political regime and seeks to transform society such that resource use and throughput are drastically reduced (Kallis et al. 2018). However, it has been noted that these approaches face significant political and social barriers, where the lack of public knowledge around these pathways and the consistent growth imperatives of states make considerations of such approaches nearly infeasible (Kallis et al. 2018; Wiedman et al. 2020). Additional barriers to the degrowth paradigm include the potential for the approach to impact the availability of affordable housing, options for mobility, and employment where the need for these basic services requires increased development. A last barrier to consider as well is advertising, where the current neo-liberal conditions under which much of the global economy operates are often empowered by the in-charge capitalist regimes (which often have a disproportionate influence and an imperative to further drive consumption) (Pirgmaier and Steinberger 2019; Alexander 2015; Sanne 2002). Such challenges to these regimes are why socio-technical transitions refer to movements such as a change to a degrowth approach as disruptive, due to the threat they present to the economic and business positions of the existing regimes (Geels et al. 2017).

This is particularly relevant to the transport sector, where the "specific character of domination" of the automobile industry upon society is difficult to argue (Urry 2004), with the total car fleet already beyond 1 billion vehicles (Sousanis 2011). The environmental ramifications of this domination were already elucidated upon in the Introduction section of this thesis. Thus, the discussion here will move forward with the acknowledgement that car-dependent regimes are a key-enabler for escalated need-satisfaction and the associated difficulty in decarbonizing and reducing material and energy use in the transport sector (Mattioli 2016). Instead, elucidated here will be the challenges associated with implementing an ecological ceiling for the transport sector, due to automobile dependence and the surrounding socio-technical system, which has shown itself to be an autopoietic system and notoriously locked-in due to features of the system (Urry 2004; Mattioli et al. 2020). As noted by Mattioli et al. (2020), the transportation sector continues to this day to be a paradigmatic example of a sector in which improvements in efficiency have been offset by activity growth, first identified by Grübler (1998). This activity growth has been a symptom of a socio-technical system of interrelated enabling actors and systems -- which have been discussed throughout this thesis -- that include, but are not limited to, the powerful automobile manufacturers and surrounding industries, car culture and associated perceived social value, transportation infrastructure lock-in, ties to the energy industry and supportive pro-car policies and political systems (which can be attributed to the economic value of the sector amongst a variety of other reasons) (Mattioli et al. 2020; Mattioli et al. 2016). This system of interrelated factors acts as a barrier to the ability to move towards an intergenerationally sustainable urban mobility system which can exist within the PBs because of its interdependence generating lock-in. Research focused on understanding how to unfasten this weave of aspects to generate a socio-technical transition has been an imperative and one that will undoubtedly continue as this change-resistant issue continues to present itself.

Limitations and weaknesses to the Planetary Boundaries framework

Relevant to the discussion surrounding the barriers associated with the implementation of ecological ceilings is the consideration of some of the limitations and weaknesses associated with the PB framework itself. While the framework has been discussed globally and championed rhetorically, it has been limited in its inclusion in international policy works. Whilte it has, at times, guided the formulation of policy -- such as the Rio +20 outcome or the 2030 Agenda, which put forward the SDGs -- it is seen as having important limitations, which can be loosely categorized as economic, political, and scientific (Pickering and Persson 2019; Bierman and Kim 2020).

Perhaps most related to the discussion surrounding the barriers to implementing ecological ceilings are the economic concerns/weaknesses. One of the primary implications of the PBs is the need to limit human pressures on them, which are ultimately tied to human production and the global economy representing this production. Thus, to stay within the PBs the need to limit economic growth is paramount, though, as discussed, this movement away from a growth paradigm is near impossible. One particular additional perspective worth adding is the global economic inequality implications associated with limiting economic growth, where the thought that economic growth of developing countries could and should be restricted (many which are the least responsible for humanity's transgression of the PBs) and associated potential development makes international environmental negotiations involving the PBs more difficult (Linnér and Henrik 2013). Degrowth literature attempts to emphasize that it does not demand (or focuses on) restricting growth in developing countries, rather it aims at contracting economies in the global North and allowing room for growth elsewhere (Hickel 2018; Hickel 2020). However, at times this nuance can be lost and international debates frequently run into these "right to development" hurdles (Gupta 2012; Caney 2009).

These debates interconnect to the second category of limitations to the PBs discussed here, namely, politics. It has been suggested that the expert-driven nature of the framework is undemocratic and lacking in its participatory approach (Pickering and Persson 2019), and this can thus make it politically contentious, with some fearing its ability to disenfranchise the masses by scientists and technocrats (Eckersley 2017). These fears of centralization and control can be largely tied to the governance implications associated with using the PBs as a guiding framework (Biermann 2012). SCC and similar frameworks thus suggest participatory frameworks to assuage these fears.

The multiple layers of the PBs (with some being local, regional, or global) and the need to address them at these different levels while simultaneously requiring global cooperation make operationalizing and governing them at a global scale a significant hurdle (Saunders 2015). This global cooperation only gets made more challenging when differing risk perceptions exist as well, where what can be perceived as an acceptable change can vary by country, particularly at differing levels of development (Galaz 2012). These varying risk perceptions can make setting globally agreed-upon targets difficult, thus making global action plan setting even more complicated. While there have been a multitude of studies that suggest different governance structures to address these issues, attempting to cover them now is outside the scope of this thesis but can be found elsewhere (Saunders 2015; Galaz 2012).

The final category of concerns regarding the use of PBs can be considered to be of the scientific variety. One of the most commonly noted limitations, even identified by the authors of the Rockström et al. (2009) paper which set the boundaries, are that they are inherently expert-driven and normative, connected to perceptions of human risk in the sense that they identify states humanity likely *would not want* (Kallis et al. 2019). It is not to say, however, that the Earth would not be able to undergo such changes nor that they would unquestioningly cause inhospitable conditions for humanity (Steffen et al. 2011). This expert-driven process thus makes it obvious that these numbers are more estimates than exact boundaries (Molden 2009), with some papers even suggesting that exponential shifts in terrestrial systems have not been seen in previous evidence (Brooks et al. 2013). The second primary scientific concern surrounds the use of the PB framework and its potential to lead to misinterpretations of their meaning and potential to impact policy. One of the most commonly cited examples is the selection and use of the phosphorus boundary, where two issues with phosphorus are commonly discussed, one being the impact on water systems and the second to the limit to the amount of phosphate rock available for use of fertilizers. Yet, in this example, the PBs do not distinguish between thresholds and limits and this lack of distinction can lead to differing responses. For example, where the phosphorus PB only measures phosphorus flow to water systems, defining the PB as a threshold would lead to responses to the address water table pollution. Yet with phosphate being a finite resource, a PB represented as a hard limit would rather look towards a more rationed consumption, which may have been argued to be equally relevant when discussing phosphate use (Carpenter and Benntr 2011; Lewis 2012). Additionally, the aggregation of local and regional impacts may misrepresent our performance, where for example the portion of land we have already impacted is significant and can be hidden in the aggregated number (Brooks et al. 2013). Treating them as a single unit could lead to misgovernance, as using an aggregated global number could reduce local political will (Lewis 2012). Furthermore, the omission of other planetary issues such as planetary plastic pollution could lead to political agendas with sustainability gaps on issues that still affect our well-being. Thus, some studies have suggested that, while useful, researchers and policy makers should proceed with caution when operationalizing the PBs (Lewis 2012). The last scientific limitation noted here are the onto-epistemological implications of the PB framework itself and recognition of the limitations of human knowledge. Röckstrom et al. (2009) themselves recognize that "The knowledge gaps are disturbing", in relation to humanity's current ability to analyze the risks and uncertainties associated with the setting of global thresholds and understanding their implications. Hughes et al. (2013) further stress this point, where while it is acknowledged that a precautionary approach is warranted to avoid a potential disaster, certainty about tipping points can rarely be proven until the changes already occur. Thus, debates on either side about planetary tipping points are based on limited knowledge and should be discussed as such, though the logic of the precautionary approach persists, where the dangers of increased carbon emissions, for example, are widely accepted though the tipping points uncertain (Brook et al. 2013; Lenton and Williams 2013).

Challenges and barriers to the implementation of social foundations

The barriers and challenges just discussed encompassed the challenges in implementing the ecological ceiling for humanity to live in a ‘safe’ space. Included in both Raworth's Doughnut Economy and the SCC framework, however, is not just the ability to live in a ‘safe’ space, but also a ‘just’ one. However, similar to defining an ecologically safe space, and perhaps even more so, defining a just space can be a daunting task. While there has been work to more clearly move from high levels of needs and capabilities to more specific decent living standards (see Rao and Min 2018 and Milward-Hopkins et al. 2020), this work is still in rather nascent stages.

Further, in the broader justice literature, the definition of justice and the implications of different forms of justice can lead to at times ambiguous and diverging solutions which can make the implementation of a social foundation difficult. In Bierman and Kalfagianni’s (2020) framework to allow for empirical assessments of justice for a variety of uses, though they used it to assess global sustainability policy documents, they reviewed five definitions of justice (namely: the capabilities approach, liberal egalitarianism, cosmopolitanism, libertarianism, and critical perspectives, which still only represent a broad yet incomplete subset of justice perspectives). Each of these definitions have their own historical use and countering debates, and when placed together within the assessment framework, they present a range of divergent core perspectives for assessment such as serving the interests of nations vs. global society, personal obligations vis-à-vis others, and rational vs. moral arguments, free market vs. welfare provisioning (of different varieties), and global institutions vs. libertarianism, amongst others. Their work takes no stance on which perspective is correct, and rather was a framework to assess which approaches are being taken in global policies. Their case study using this framework on the UN 2030 Agenda for Sustainable Development (2015) made it clear why justice is such an elusive subject, where even though terms justice and equality are widespread throughout the document, their application of justice approaches is inconsistent. In their assessment, they found that the Agenda rhetorically seemed to take a cosmopolitan approach to justice, yet in terms of political mechanisms, there appeared to be a more soft-libertarian leaning, likely due to the nature of international negotiations with differing global perspectives of justice. This can be seen as well in Röckstrom’s (2021) work, where globally differing perspectives of risk tolerances and ecological justice could lead to different conclusions of what would be considered a just space for all, versus what might be considered just for ‘most’ amongst other interpretations of ‘just’ risk.

Moving this debate down to the transport sector, Pereira et al. (2017) performed a distributive justice assessment of the mobility sector, similar to Bierman and Kalfagianni (2020), using a similar, though not entirely overlapping, subset of five justice approaches. They found that in transport justice studies in general there was a lack of conceptual clarity of justice (similar to the findings of Bierman and Kalfagianni in terms of policy documents), and that this lack clarity made cross-study comparisons of transport justice studies difficult. Pereira et al.’s conclusions, however, were that a dialogue of Rawls’ egalitarianism and the capability approach should be used when considering distributive justice in the transport sector, with accessibility as the factor which should be distributed. Yet, as discussed by Paez et al. (2012), accessibility indicators themselves represent a field with significant inconsistencies, where there is often an unclear distinction between those indicators measuring what *ought* to be, and what *is*. Additionally, the appropriate distance to access each service has been seen to an arbitrary measurement, often derived from previous literature. Furthering this discussion to transport poverty, in Mattioli et al.’s (2017) discussion deciphering between transport poverty and energy poverty, inconsistencies and difficulties in determining a social foundation for transport poverty additionally proved to be a challenging task. Adding to this the cultural and contextual differences between regions and different transport modes available which define many of these indicators, the challenges of setting a social foundation in general show themselves, especially for the transport sector since it does not represent the satisfaction of a need in itself. Addressing justice is an important task however, both for normative and policy reasons, where a democratic and well-developed just approach can hopefully reduce policy resistance or dissent amongst different populations groups as well as accelerate change (Schwanen 2021). Schwanen (2021) has thus suggested that when attempting to address these cultural and contextual sustainability transitions in transport, the approach should focus on distributional, procedural and recognition justice should be had, to accelerate these transitions with minimal social friction due to the inclusive and democratic approach that should be taken.

4.3 Evaluation of the study

Within every study, there are inherent limitations, and this study is no different. Within each of the papers that constitute the basis of this thesis, the limitations of the individual study are discussed and for brevity's sake, will not be repeated here. Therefore, for those interested in the limitations of the individual results from each paper, this thesis guides the reader to the discussion sections of each, where the limitations related to the associated paper's findings can be found. Alternatively, discussed here is the reliability and applicability of this study, through the context of the interpretation of the results of the four papers and positioning them within the literature. Breaking these interpretations into three key perspectives, the scope of the study and its implications, systemic changes, and rebound effects are discussed, all of which could potentially impact the validity of the results.

4.3.1 Scope

In the multi-scale approach taken in the study, EVs were first studied at a product level. At this product level, it is worth identifying that the results only incorporated results from medium-sized passenger vehicles, as identified in the selection of the review material in Paper I. This approach was taken to avoid increased variability in the results due to the incorporation of multiple vehicle types. This, however, lacks the conversation around SUVs (and also light vehicles), which in the EU and China are the fastest-growing market segment and are already the largest market segment in the U.S. (IEA 2021). SUVs have been noted for their higher embedded emissions and resource use and lower efficiency than smaller vehicles due to their increased size and material use (Karaaslan et al. 2018), thus mentioning their exclusion is relevant.

With the urban level as the core spatial perspective of this thesis, and, particularly, the study's focus on urban-level passenger ground transport, it is highly relevant to place these scopes into the correct context. This scope was chosen intentionally since cities can act as key macro-level actors and they are increasingly housing a growing percentage of the global population. Additionally, from a social perspective, in the interest of understanding how EVs fit into the larger role of mobility as a basic public service and means to satisfy human needs, focusing on passenger ground transport based on urban travel demand was deemed to be justified, where freight and flights were considered outside of the scope of the study.

The importance of the environmental impacts of these exclusions is not lost on this study, particularly given the impacts of freight both in terms of GHG emissions as well as the potential grid impact of attempting to electrify a freight fleet. In particular, for GHG emissions this again may represent an underestimate, where Savy and Burnham (2013) estimated that the exclusion of freight could lead to underestimates of up to 50% in urban transport estimates. Further studies have additionally identified the importance of transport infrastructure emissions (Chester and Horvath 2009), which, in the context of this study, could include roads, charging infrastructure for EVs, and the life cycle emissions associated with supporting electrical infrastructure that could be required to maintain the electrical grid with increased EV demand. Additionally, when considering the difference between behavioural change scenarios that suggested increased densification, the infrastructure emissions required to facilitate increased densification could be a significant source of emissions (Pomponi et al. 2021). Lastly, this study only considered emissions from intra-urban transport and did not consider transport between cities nor air transport. These emissions are still relevant to the transportation sector, where it has been seen that, particularly for urbanites, transportation emissions from air travel are increasing rapidly and becoming a growing portion of city dwellers' transportation emissions (Czepkiewicz et al. 2019). Lastly, the previously mentioned exclusion of SUVs additionally extends to the urban level GHG assessment, and thus the impact of higher car fleet sizes which was identified as a key factor in the increased indirect GHG emissions could potentially be underestimated.

Therefore, in terms of scope, readers must understand the scope of the results and their potential shortcomings, where this study focused specifically on mid-sized vehicles in the urban ground passenger transportation sector, which was considered to be the relevant and achievable scope of the study. This understanding can be broken into 1) how the limitations and boundaries of this scope affect the actual results of the study and 2) how they affect their interpretations and implications. In terms of actual results, the omission of SUVs represents a simplification and could potentially lead to an under-representation of both the direct and indirect urban-level GHG emission estimates (where SUVs have lower fuel efficiencies and higher material use in production) in the results in Paper II. The rest of the identified scope-relevant limitations refer more to how the results can and should be interpreted. For example, the results of this thesis should not be used to characterize the GHG profile of the greater mobility sector, where freight, flights, and long-distance transport serve different purposes than serving local travel demand, which was the focus of this study. Additionally, the lack of life cycle emissions associated with infrastructure (including roads, potential electrical grid and capacity expansions, EV charging infrastructure, bus stations, etc.) and urban form changes represent often difficult to quantify impacts at the urban scale and make comparing the GHG implications of certain development pathways more challenging. Thus, while these changes were established as outside of the scope of the study, this study acknowledges the uncertainty associated with actual GHG emissions of urban sprawl as opposed to a more densified form (where one may require greater road provisioning and the other greater redevelopment and high-rise development) as well as EV infrastructure expansion. The more future studies can incorporate the additional impacts of these infrastructural changes, the more accurately the GHG implications of different development pathways can be characterized.

It is additionally worth noting the potential shortcomings associated with the scale leap from city to global sustainable mobility taken in this study. With the emphasis placed on cities, the risks of taking a methdologically "cityist" approach present themselves (Angelo and

Wachsmuth, 2015). With too tight a focus placed on the city itself, isolated from the larger national, international, and in the other spatial scale, hyper-local contexts, the narrowed focus of cityism can lead to unrealistic conclusions being drawn, due to the potentially significant impact of these surrounding contexts. Further, with the blurred lines of what delineates a city as a specific site and the surrounding space, where Brenner and Schmid (2015) even argue the 'urban' to be more a theoretical abstraction than a concrete object, a cityist approach can even struggle in capturing its own scale appropriately. Where a city, in the sense of a governing entity, may be define itself within strict geographical limits, urban activities rarely act within in these limits, and such a distinct focus on the city as opposed to the urban (or lack of distinction) presents a risk of further missing context within its own approximate spatial scale. These issues extend for global comparative urban studies which threaten to devalue the highly varied contexts of the individual cities, often lacking a means to normalize the results (Robinson, 2016). Angelo and Wachsmuth (2015) acknowledge that there is nothing inherently wrong with the cityist approach, but rather the lack of acknowledging its limitiations in the literature to be the most pressing issue. Thus, it is worth noting in this work Reykjavik's multi-scaled existence as a city within Iceland, a country which is part of the European Economic Area, and thus subject to the context of both of these conditions. For example, mobility, urban, and policies implemented at the supranational E.U. level could lead to impacts on Reykjavik and the city's mobility system, as the city does not exist in isolation of these factors.

4.3.2 Systemic changes

Whilst evaluating this study, the limitations of what can be understood on a systemic scale also needs to be considered, particularly when considering the long-term temporal aspects associated with scenario modelling in this study. Included within this grouping are systemic changes associated with Covid-19 (and potentially future unknown pathogens), technological developments, and changing political landscapes, though these are but a few of the most relevant systemic changes amongst a long list of changes that could potentially impact the results of the study.

The first of these changes involves Covid-19 and the potential long-term societal changes it and future pathogens may bring. The pandemic caused significant changes to both local and long-distance travel behaviour, though the longevity of these changes remains to be seen (Siddique et al. 2021). Additionally, what changes will continue forward are difficult to predict. While many expect remote working to continue beyond the pandemic, thus leading to less commuting and energy consumption from transport, it may also lead to less inclination to take public transport in the short term, leading to greater private vehicle use (Zhang and Zhang 2021). How these trade-offs will affect travel patterns and associated emissions in the long term remains to be seen, and thus could potentially impact the validity of the results as travel behaviour in both Paper II and Paper III were modelled from a pre-covid travel behaviour survey (Gallup 2017). This does not even take into the potential changes to urbanization and densification that these changing behavioural patterns due to the pandemic may bring. Future works should thus take these potential changes into account when modelling travel behaviour in the future.

Many of the transformations which allowed society to transition to the "new normal" of teleworking and digital schooling were enabled by technology that perhaps would not have been available just a decade or two ago. The pace of digitalization and modern technology development and its ability to impact urban development has shown itself in the smart city movement and is likely to continue. How technology will transform the transportation sector in the long-term is difficult to model and predict, where many of the Mobility-as-a-Service and shared vehicles (Cruz and Sarmento 2020; Sperling 2018), last-mile solutions (Miles et al. 2016), and Automated Vehicle (AV) technologies (Hancock et al. 2019) are still in nascent stages, and how they will affect the transportation sector remains to be seen. Additionally, surrounding EVs and alternative vehicles, batteries, smart charging, vehicle-to-grid (Heinisch et al. 2021), and vehicle-to-X technologies (Kobashi et al. 2020), energy efficiency, and other alternative fuel developments (such as hydrogen and biofuels) will further impact the pace at which decarbonization in the transportation sector occurs, both for passenger vehicles as well as for heavy-duty vehicles such as busses and trucks (IEA 2019; IEA 2020). While technological developments were considered within Paper II's models, these are, of course, subject to a significant amount of near unavoidable technological uncertainty. Larger macro-level developments in the energy sector in general, which supplies the necessary energy for transport, both renewable and nonrenewable, are additionally subject to both technological and economic developments (such as wind and solar installation costs, energy storage technology developments, fossil fuel price fluctuations, etc.) that could also impact the rate at which renewable energy technologies are adopted as well as affect the uptake of EVs (where, for example, volatile fossil fuel prices could either encourage or discourage EV purchases). These developments could impact both the rate of integration of EVs in these studies as well as change the modal shares of travel behavior within Papers II and III, thus adding additional layers of uncertainty to the results.

Changing political landscapes could additionally impact the results of the study in the sense that they could alter the political will to achieve some of the developments discussed in the study as well as what might actually occur as compared to the scenarios. With the newest IPCC (2021) and WMO (2021) reports emphasizing the increasing likelihood of hitting 1.5°C warming within this century, it could be that as the impacts of climate change continue to grow, what was once considered to be politically infeasible may quickly become mainstream as the general public increasingly demands action from their respective states. Alternatively, however, nationalism/populism (Kroll and Zipperer 2020; Marschall and Klingbiel 2019), polarization and politicization of environmental agendas (Sintov et al. 2020), and potential geopolitical strife, disagreements, and refusal to negotiate could lead to weakened international cooperation and political will, as seen in the U.S.'s withdrawal from the Paris Agreement (Zhang et al. 2017). Further, large scale socio-technological changes would, if not require, certainly lead to, transitions from the incumbent dominant regimes who may not want to cede their held powers to newcomers within this transition and even have vested interest in stopping them, such as multi-national corporations (i.e. the fossil fuels industry). These power relations and how they may resist these transitions, influence politicians, and change over time could have a great impact in our abilities to make such strong-state sustainability transitions (Brand et al. 2020). Such issues could hamper the international climate agenda and slow sustainable development geared policies and associated socio-technical transitions, such as the integration of EVs (Pirgmaier and Steinberger 2019).

4.3.3 Rebound effects

Additionally important when evaluating the study is the potential for rebound effects. In the field of environmental study, rebound effects are the potential unintended consequences of certain policies or shifts in consumption which can lead to negative impacts through increased consumption or emissions (Ottelin 2016; Allan et al. 2009). Brockway et al. (2017) further categorize these rebound effects into micro and macro economic rebound effects, which describe the static (such as income, substitution, embodied energy, and re-spending effects) and dynamic (such as economy-wide and transformational effects) changes rebound effects can have on the economy, respectively. Such rebound effects from systemic changes were broken up here into the two categories: 1) those which could potentially impact the results of the study, and 2) those which could potentially be seen outside of the scope of the study that readers should be made aware of.

In the first group of rebound effects which could potentially impact the results of the study, a first example can be connected to an efficiency-related/velocity-related rebound effect, whereby more efficient public transport modes such as high-speed trains might actually lead to greater travel demand (Spielmann 2008). Such an efficiency-rebound effect could potentially be seen economically as well, where, for example, as fuel efficiency improves and the cost per kilometre of driving decreases, the greater driving demand may be, leading to increased consumption (De Borger et al. 2021). Both such effects could lead to misrepresentation in the temporal models, where the rebound effects caused by technological and efficiency improvements could lead to greater consumption than expected based on current trends.

In the second grouping of rebound effects, which may not be seen in the scope of the study but could still be relevant to the results, a first example also includes an economic perspective; taking either an EV or greater public transport/active transport mode centric-approach, as affordability of transport goes up and urban dwellers spend a proportionally lower share of their income on transport, their ability to spend and consume more rises. If this freed-up money is then spent on goods/services with a higher environmental impact, this could lead to increased effects. Conversely, densification and reduced car ownership (and reduced associated costs of ownership) may lead to other rebound effects such as the greater taking of flights and other forms of consumption (Czepkiewicz et al. 2018; Ottelin et al. 2017). Lastly, from a global intergenerational sustainability perspective, when considering potential per capita environmental ceilings, urban transport is only one consumption sector, where, for example, Akenji et al. (2019) included additional sectors such as nutrition, goods and services, and housing. One potential rebound effect and risk of considering only one sector is that from the perspective of an EC, if one were able to decrease their impacts towards the EC in one sector, this may be used as a justification to increase it within another consumption sector, rather than attempting to minimize the impacts as possible. With these rebound effects identified, it is thus important for future studies both focused on the mobility sector as well as other consumption sectors and other environmental assessments to consider the different relevant rebound effects and their implications associated with densification, EV integration, and the changing economics of the transportation sector which can affect consumption.

4.4 Future research directions

Considering the findings, limitations, and barriers identified by this thesis, there remains a wide range of future research to address these issues. Individually, each paper within has identified areas for future research regarding their specific fields of study, and thus, for the sake of redundancy, this paper will guide the readers to those papers for greater detail regarding the individual topics of the papers. Alternatively, this work will take a broader perspective, integrating the combined results from all the studies to suggest which areas of future research the holistic results suggest. Taking this approach, three general interrelated fields of future research of particular interest were identified.

4.4.1 Integrated transformation pathway development and mapping

The first area of future study identified was the development of a multi-criteria decision assessment (MCDA) and/or system dynamics tools for decarbonization as well as more holistic sustainability pathway development, which would consider environmental and social criteria within the context of an SCC. Additionally, with the discussion surrounding the importance of context in path dependence and different types of lock-ins (Rode et al. 2014; Mattioli et al. 2020), yet in line with Figure 16, the extent to which these lock-ins exist according to regional contexts are often unknown. This research thus suggests an approach in which ASI and social provisioning strategies are considered across sectors (similar to Akenji et al. 2019; Ivanova, et al. 2020), and their potential effectiveness/ability to be influenced be assessed according to the regional context (such as accessibility, population density, electrical grid GHG intensity, the potential for EV integration, etc.). Performing such an assessment using LCA meta-analysis, policy assessments, and policy pilot studies, an MCDA and/or system dynamics model could be developed such that SCC compliant development pathways could be suggested. State and city officials, urban planners, and researchers could use such assessments to develop adaptive plans according to their regional contexts. Such models taking this regional context and data are rare, and through robust and flexible development of the work, adaptable regional insights into SCC pathway development could be provided, which would be a useful addition to the research. Such developments in ASI and social provisioning strategies, their connection to lifestyle footprints and environmental impacts and their potential for sustainable development at different spatial levels national/subnational have been called for in the literature (Akenji et al. 2019). These works should follow a participatory approach and the inclusion of diverse stakeholders to ensure a democratic process with greater success of implementation probability as suggested by SCC works and other social justice literature (i.e. Fuchs et al. 2021; Pereira et al. 2016; Schwanen 2021).

4.4.2 Sustainable consumption’s contextual relevance

Taking the contextual relevance discussed, this study has found that a greater understanding is needed surrounding sectoral trade-offs and different international contexts in discussions surrounding sustainable consumption corridors (and the implied effects of intergenerationally sustainable consumption), especially between the global south and global north (Wiedman et al. 2020). The barriers to the implementation of SCCs and setting ecological ceilings have been discussed, and taking these into account, future research can seek to understand which drivers can move societies towards an SCC and elucidate what behaviour and technological changes would be needed across sectors to achieve intergenerational sustainability. If the GDP growth imperative was abandoned as a goal to achieve movement into the SCC, what would this mean for the economy and social stability? Additionally, how would GDP growth abandonment affect the social outcomes of developing countries? What level then would be just to respectively restrain developed and developing countries environmentally to ensure PB alignment whilst at the same time allowing for socially acceptable outcomes in both categories of countries? How would these changes then impact the economy and social stability (see Büchs and Koch 2019)? How would it affect trade and the global south? How does the impact of each sector change according to the local and regional contexts (i.e. can a country with lower energy grid GHG intensity equitably have greater transportation emissions?)? While degrowth and other such literature have discussed these questions qualitatively, quantitative assessments understanding these trade-offs and their connections to our ability to live within an SCC at a sector level have been limited [though examples such as Jackson and Victor's (2016) work exist at an economy-wide scale] and may miss some of the sectoral granularity which could provide greater insights for decision making.

4.4.3 Development of SCC-relevant indicators

An extension of the considerations surrounding future research of SCCs is the development of sustainable consumption relevant indicators and thresholds, both from environmental and social perspectives as well as from an integrated perspective of the two. Environmentally, underrepresented in SUM indicator literature is a focus on the scale of impacts and their relations to the PBs, not just efficiency or incremental improvement (Holden et al. 2013). While a plethora of environmental SUM indicators exist, the lack of connections to thresholds tends towards 'weak sustainability' or a more a directional movement towards sustainability as opposed to attempting to reach an intergenerationally sustainable state. Thus, this research suggests that there should be a greater focus on understanding the mobility sector's role within the PB's and when integrated with other consumption sectors and emissions sources. A research gap exists in understanding what role the mobility sector can and could play in the consumption profile of a region, and how that may change in different contexts. Indicators that connect to these thresholds can assist in providing the numbers necessary to make these types of assessments. From the social perspective, while accessibility indicators have been discussed for some time (Morris et al. 1979; Koenig, 1980; Chen et al. 2011), as Páez et al. (2012) point out, the distinction between how things are and how things ought to be are often lost. As Páez et al. point out, studies often silo these two approaches, which makes tying the two together difficult, signifying a lack of connection between indicators (of how things are) and thresholds (of how things should be).

An additional challenge to such a normative approach is determining what would define an acceptable level of SFs such that it would suggest the ability to live a 'good and dignified' life. Research is increasingly considering the provision of Universal Basic Services, which incorporates transport as a basic service (Coote, 2021). Thoughts about transport justice similar to the approach taken by Pereira et al. (2017) could be combined with social sustainable urban mobility indicator works in an attempt to link just approaches and the measurements of these issues. Future research could investigate these topics through various participatory and stakeholder approaches to ensure procedural justice and to understand the needs and requirements of different user groups in different contexts (Schwanen 2021). Translating these needs to more granular SFs and indicators would then assist in developing a more granular and useful SF.

Lastly, the SCC perspective presents an opportunity for the creation of integrated environmental-social indicators for different sectors. This integrated perspective can tie together the ECs and SFs such that the two become interrelated for different sectors, for example, in the mobility sector, through the creation of indicators that describe the GHG emissions associated with access to a certain service. This added perspective shift could assist in determining what level of access to services and mobility would be needed to stay within the ECs as well as measuring the performance of the system. Integrating these perspectives could work to push past the intellectual dead-end identified in transport studies (Grossmann et al. 2021), where social justice transport studies often identify the environmental shortcomings seen in the works and the same occurs vice-versa in environmentally-focused transport studies.

5 Conclusion

This thesis took a multi-scale approach to understand the role that EVs could play in the development of a sustainable urban mobility system and then placed their developments within the much broader context of intergenerational sustainability through the use of SCCs. With the international focus on utilizing EVs as a leading solution to decarbonize transport and at times consumer uncertainty surrounding the ability for EVs to lead to environmental benefits, this thesis first focused on understanding EVs' GHG impacts on a product and system level. This work found that at a product level, within almost all electrical grid GHG intensity contexts and low to medium contexts for petrol and diesel cars, respectively, EVs led to less life cycle GHG emissions, where the scale of the difference was dependent on the intensity of the grid. However, at an urban systems level, due to the higher embedded emissions associated with EVs, from a perspective incorporating both direct and indirect emissions, in the case study performed on Reykjavik (which represents a near best-case scenario for EV use in terms of life cycle GHG emissions), it was found that a behavioral transformation with greater use of public and active transport would lead to similar if not less cumulative GHG emissions than a technological EV-centric GHG development pathway. Additionally, this work showed that this greater incorporation of EVs would lead to greater electrical demand and peak load impacts if car fleet size and charging are not controlled.

Addressing the RQ3 regarding the characterization of a mobility-focused SCC led to developments that provided a good context for discussing the implications of the results from Paper I-III, where it was made clear in the integrated results that if intergenerational sustainability is to be achieved, a perspective shift will be required. While many national and international urban transport decarbonization initiatives tend to pose the question of, "how can we transform our mobility system to incorporate this solution (EVs) to become more sustainable?", this thesis suggests that this line of questioning is directionally flawed. Instead, with the goal of intergenerational sustainability in mind, the question should rather be posed as, "how can we transform and utilize a suite of solutions (EVs, public transport and public transport modes, urban transformation, digitalization) and incorporate them into the urban mobility system to maximize accessibility and minimize environmental impacts?" Rather than leading with the fix and solution and using that to define the system state (which could potentially lead to further lock-in of car dependency), this thesis suggests the reverse, where first the desired system state should be defined, and then, according to the context of the system, the correct and relevant set of solutions be implemented.

References

ACEA (2021), Vehicles in use Europe, ACEA, https://www.acea.auto/files/report-vehicles-in-use-europe-january-2021-1.pdf

Adhikari, M., Ghimire, L. P., Kim, Y., Aryal, P., & Khadka, S. B. (2020). Identification and analysis of barriers against electric vehicle use. *Sustainability*, 12(12), 4850.

Akenji, L. (2014). Consumer scapegoatism and limits to green consumerism. *Journal of Cleaner Production*, 63: 13-23. https://doi.org/10.1016/j.jclepro.2013.05.022.

Akenji, L., Lettenmeier, M., Koide, R., Toivio, V., & Amellina, A. (2019). 1· 5-degree lifestyles: targets and options for reducing lifestyle carbon footprints. *Institute for Global Environmental Strategies*: Hayama, Japan.

Alcott, B. (2014). Jevons' paradox. In *Degrowth* (pp. 149-152). Routledge.

Alexander, S. (2015). *Sufficiency Economy.* Simplicity Institute.

Allan, G., Gilmartin, M., McGregor, P. G., Swales, J. K., & Turner., K. (2009). Modelling the economy-wide rebound effect. In *Energy efficiency and sustainable consumption* (pp. 69-98). London: Palgrave Macmillan.

Anable, J., Brand, C., Tran, M., & Eyre, N. (2012). Modelling transport energy demand: A socio-technical approach. *Energy Policy*, 41: 125-138.

Anderton, A. (2000). Economics. 3rd edition. Ormskirk, UK: Causeway Press.

Angelo, H., & Wachsmuth, D. (2015). Urbanizing Urban Political Ecology: A Critique of Methodological Cityism. In *Implosions/Explosions* (pp. 372-385). JOVIS Verlag GmbH.

Arvizu, D. T., Chum, H., Edenhofer, O., Estefen, S., Faaij, A., Fischedick, M., . . . Zwickel, T. (2011). Technical summary. In IPCC special report on renewable energy sources and climate change mitigation. *IPCC*.

Barcelona Regional. (2021). *L'Economia Dònut a Barcelona.* Barcelona: Barcelona Regional.

Berkeley, N., Jarvis, D., & Jones, A. (2018). Analysing the take up of battery electric vehicles: An investigation of barriers amongst drivers in the UK. *Transportation Research Part D: Transport and Environment*, 63, 466-481.

Biermann, F. (2012). Planetary boundaries and earth system governance: Exploring the links. *Ecological Economics*, 81: 4-9.

Biermann, F., & Kalfagianni, A. (2020). Planetary justice: A research framework. *Earth System Governance*, 6: 100049. doi.org/10.1016/j.esg.2020.100049.

Biermann, F., & Kim, R. E. (2020). The boundaries of the planetary boundary framework: a critical appraisal of approaches to define a "safe operating space" for humanity. *Annual Review of Environment and Resources*, 45: 497-521.

Biresselioglu, M. E., Kaplan, M. D., & Yilmaz, B. K. (2018). Electric mobility in Europe: A comprehensive review of motivators and barriers in decision making processes. *Transportation Research Part A: Policy and Practice*, 109, 1-13. doi.org/10.1016/j.tra.2018.01.017.

Boisjoly, G., El-Geneidy, A., & Serra, B. (2021). Avoiding public transport? Assessing the relationship between accessibility, income and commuting mode in Recife, Brazil. In M. N. Mladenović, T. Toivonen, E. Willberg, & K. T. Geurs, *Transport in Human Scale Cities.* Edward Elgar Publishing. doi.org/10.4337/9781800370517.

Boutueil, V., & Aguilera, A. (2018). Impacts and Challenges for Developing Countries. In *Urban Mobility and the Smartphone: Transportation, Travel Behavior and Public Policy* (pp. 169-199).

Box, G. E., & Draper, N. R. (1987). *Empirical model-building and response surfaces.* John Wiley & Sons.

Brady, J., & O'Mahony, M. (2016). Modelling charging profiles of electric vehicles based on real-world electric vehicle charging data. *Sustainable Cities and Society*, 203-216.

Brand, C., Anable, J., & Morton, C. (2019). Lifestyle, efficiency and limits: modelling transport energy and emissions using a socio-technical approach. *Energy Efficiency*, 12(1)): 187-207.

Brand, U., Muraca, B., Pineault, É., Sahakian, M., Schaffartzik, A., Novy, A., Streissler, C., Haberl, H., Asara, V., Dietz, K. and Lang, M. (2021). From planetary to societal boundaries: an argument for collectively defined self-limitation. *Sustainability: Science, Practice and Policy*, 17(1), pp.265-292.

Brand-Correa, L. I., Mattioli, G., Lamb, W. F., & Steinberger, J. K. (2020). Understanding (and tackling) need satisfier escalation. *Sustainability: Science, Practice, and* Policy, (16)1 309-325 https://doi.org/10.1080/15487733.2020.1816026.

Brockway, P. E., Saunders, H., Heun, M. K., Foxon, T. J., Steinberger, J. K., Barrett, J. R., & Sorrell, S. (2017). Energy rebound as a potential threat to a low-carbon future: Findings from a new exergy-based national-level rebound approach. *Energies*, 10(1), 1–24. https://doi.org/10.3390/en10010051

Brook, B. W., Ellis, E. C., Perring, M. P., Mackay, A. W., & Blomqvist, L. (2013). Does the terrestrial biosphere have planetary tipping points?. *Trends in ecology & evolution*, 28(7), 396-401.

Büchs, Milena, and Max Koch. "Challenges for the degrowth transition: The debate about wellbeing." *Futures* 105 (2019): 155-165.

Camagni, R., Capello, R., & Caragliu., A. (2013). One or infinite optimal city sizes? In search of an equilibrium size for cities. *The Annals of Regional Science*, 51:309–341. DOI:10.1007/s00168-012-0548-7.

Caney, S. (2009). Justice and the distribution of greenhouse gas emissions. *Journal of Global Ethics* , 5(2): 125-146. doi.org/10.1080/17449620903110300.

Carpenter, S. R., & Bennett, E. M. (2011). Reconsideration of the planetary boundary for phosphorus. *Environmental Research Letters*, 6(1): 014009.

Chen, Y., Ravulaparthy, S., Deutsch, K., Dalal, P., Yoon, S. Y., Lei, T., . . . Hu, H.-H. (2011). Development of indicators of opportunity-based accessibility. *Transportation Research*, 2255(1): 58-68.

Chester, M. V., & Horvath, A. (2009). Environmental assessment of passenger transportation should include infrastructure and supply chains. *Environmental Research Letters*, 4(2), 024008. .

Chester, M. V., Nahlik, M. J., Fraser, A. M., Kimball, M. A., & Garikapati, V. M. (2013). Integrating Life-cycle Environmental and Economic Assessment with Transportation and Land Use Planning. *Policy Analysis*, 47(21): 12020–12028 doi.org/10.1021/es402985g.

Cianci, R. and Gambrel, P. (2003). Maslow's hierarchy of needs: Does it apply in a collectivist culture. *Journal of Applied Management and Entrepreneurship*, 8(2), pp. 143–161

Cirianni, F., Monterosso, C., Panuccio, P., & Rindone, C. (2017). A review methodology of sustainable urban mobility plans: Objectives and actions to promote cycling and pedestrian mobility. *International conference on Smart and Sustainable Planning for Cities and Regions* (pp. 685-697). Springer, Cham.

City of Reykjavik. (2016). *City of Reykjavik's Climate Policy.* Reykjavik: City of Reykjavik.

City of Reykjavik. (2020). *Population in Reykjavík, the capital area and the country as a whole, 1901-2020*. Retrieved from City of Reykjavik data: http://tolur.reykjavik.is/PXWeb/pxweb/is/01%20%C3%8Db%C3%BAar/01%20%C3%8Db%C3%BAar__01.%20Mannfjoldi/IBU01001.px/?rxid=d7b02b07-2996-4f12-8241-2d4ba81a90df.

City of Reykjavik data. (2004). *„Hvað er Reykjavík margir metrar?“.* Accessed on: 13. september 2021.: Vísindavefurinn.

Clean Energy Ministerial. (2019). *EV 30@30 Campaign.* https://www.cleanenergyministerial.org/sites/default/files/2019-06/EV30@30%20fact%20sheet%20(June%202019).pdf: Clean Energy Ministerial.

Clement-Nyns, K., Haesen, E., & Driesen, J. (2011). The impact of vehicle-to-grid on the distribution grid. *Electric Power Systems Research, 81*(1), 182-192.

Commission, E.-E. (2020). *Sustainable and Smart Mobility Strategy–putting European transport on track for the future, SWD (2020) 331 final (COM (2020) 789 final).* EC.

Coote, A. (2021). Universal basic services and sustainable consumption. *Sustainability: Science, Practice and Policy*, 32-46. https://doi.org/10.1080/15487733.2020.1843854.

Costanza, R., Fisher, B., Ali, S., C., B., Bond, L., Boumans, R., . . . Gayer, D. (2007). Quality of life: An approach integrating opportunities, human needs, and subjective well-being. *Ecological Economics*, 61(2-3), 267-276.

Creutzig, F., Fernandez, B., Haberl, H., Khosla, R., Mulugetta, Y., & Seto, K. C. (2016). Beyond technology: demand-side solutions for climate change mitigation. *Annual Review of Environment and Resources*, 41: 173-198.

Creutzig, F., Roy, J., Lamb, W., Azevedo, I., De Bruin, W., Dalkmann, H., . . . Hertwich, E. (2018). Towards demand-side solutions for mitigating climate change. *Nature Climate Change*, 8(4) 260.

Croci, E., Lucchitta, B., Janssens-Maenhout, G., Martelli, S., & Molteni, T. (2017). Urban CO2 mitigation strategies under the Covenant of Mayors: An assessment of 124 European cities. *Journal of Cleaner Production*, 169, 161-177.

Crutzen, P. J. (2000). The 'anthropocene'. *Global Change Newsletter*, 17-18.

Crutzen, P. J. (2016). Geology of mankind. In P. J. Crutzen, *Paul J. Crutzen: A Pioneer on Atmospheric Chemistry and Climate Change in the Anthropocene* (pp. 211-215). Springer, Cham.

Cruz, C. O., & Sarmento, J. M. (2020). Mobility as a Service" Platforms: A Critical Path towards Increasing the Sustainability of Transportation Systems. *Sustainability*, 12(16): 6368. doi.org/10.3390/su12166368.

Curl, A., Clark, J., & Kearns, A. (2018). Household car adoption and financial distress in deprived urban communities: A case of forced car ownership?. *Transport Policy*, 65: 61-71. doi.org/10.1016/j.tranpol.2017.01.002.

Czepkiewicz, M., Árnadóttir, Á., & Heinonen, J. (2019). Flights Dominate Travel Emissions of Young Urbanites. *Sustainability*, 11(22), 6340; https://doi.org/10.3390/su11226340.

Czepkiewicz, M., Heinonen, J., & Ottelin, J. (2018). Why do urbanites travel more than do others? A review of associations between urban form and long-distance leisure travel. *Environmental Research Letters*, 13(7): 073001. doi.org/10.1088/1748-9326/aac9d2.

C40 (2021). C40 Annual Report 2020. C40. https://c40-production-images.s3.amazonaws.com/other_uploads/images/2827_C40_Annual_Report_2020_vMay2021_lightfile.original.pdf?1622806882

https://www.c40.org/wp-content/uploads/2021/11/C40-2020-Annual-Report.pdf

Daina, N., Sivakumar, A., & W.Polak, J. (2017). Modelling electric vehicles use: a survey on the methods. *Renewable and Sustainable Energy Reviews, 68*(1), 447-460.

Daly, H. E. (1977). *The steady-state economy.* na.

de Borger, B. I. (2021). The Rebound Effect for Car Transport. *International Encyclopedia of Transportation: Volume 1. Transport Economics. Elsevier*, 174-178.

De Vos, J., Schwanen, T., Acker, V. V., & Witlox, F. (2013). Travel and Subjective Well-Being: A Focus on Findings, Methods and Future Research Needs. *Transport Reviews*, 33(4): 421-442. doi.org/10.1080/01441647.2013.815665.

Dearing, A., Wang, J., Rong, Ke, Z., Dyke, J. G., Haberl, H., ..., F. E. (2014). Safe and just operating spaces for regional social-ecological systems. *Global Environmental Change*, (28) 227-238.

Di Giulio, A. a. (n.d.). The 'Good Life' and Protected Needs. In A. Kalfagianni, D. Fuchs, & A. Hayden, *The Routledge Handbook of.* London: Routledge.

Di Giulio, A., & Fuchs, D. (2014). Sustainable Consumption Corridors: Concept, Objections, and Responses. *GAIA - Ecological Perspectives for Science and Society,*, 23(1), 184-192(9) https://doi.org/10.14512/gaia.23.S1.6.

Diener, E. (2000). Subjective well-being: The science of happiness and a proposal for a national index. *American psychologist*, 55(1): 34.

Dillman, K. J., Árnadóttir, Á., Heinonen, J., Czepkiewicz, M., & Davíðsdóttir, B. (2020). Review and Meta-Analysis of EVs: Embodied Emissions and Environmental Breakeven. *Sustainability*, 12(22), 9390; https://doi.org/10.3390/su12229390.

Dillman, K. J., Fazeli, R., Shafiei, E., Jónsson, J. Ö., Haraldsson, H. V., & Davíðsdóttir, B. (2021a). Spatiotemporal analysis of the impact of electric vehicle integration on Reykjavik's electrical system at the city and distribution system level. *Utilities Policy*, (68) 101145 https://doi.org/10.1016/j.jup.2020.101145.

Dillman, K., Árnadóttir, Á., Gunnarsdóttir, I., Czepkiewicz, M., Fazeli, R., Heinonen, J., & Davidsdóttir, B. (2021b). *Decarbonization Scenarios for Reykjavik's passenger transport II: The combined effects of behavioral changes and technological developments.* Reykjavik. Accessible at: http://www.vegagerdin.is/upplysingar-og-utgafa/: The Icelandic Road Authority (Rannsóknasjóðs Vegagerðarinnar).

Dillman, K., Czepkiewicz, M., Heinonen, J., & Davíðsdóttir, B. (2021c). A Safe and Just Space for Urban Mobility - A Framework for Sector-Based Sustainable Consumption Corridor Development. Global Sustainability, 1-42. doi:10.1017/sus.2021.28

Dillman, K., Czepkiewicz, M., Heinonen, J., Fazeli, R., Árnadóttir, Á., Davíðsdóttir, B., & Shafiei, E. (2021d). Decarbonization scenarios for Reykjavik's passenger transport: The combined effects of behavioural changes and technological developments. *Sustainable Cities and Society*, (65). 102614 https://doi.org/10.1016/j.scs.2020.102614.

Doyal, L., & Gough, I. (1991). *A Theory of Human Need.* Basingstoke: Macmillan.

Dreborg, K. H. (1996). Essence of backcasting. *Futures*, 28.(9): 813-828.

Driscoll, P. A., Theodórsdóttir, Á. H., Richardson, T., & Mguni, P. (2012). Is the Future of Mobility Electric? Learning from Contested Storylines of Sustainable Mobility in Iceland. *European Planning Studies*, 20(4) https://doi.org/10.1080/09654313.2012.665036.

Eckersley, R. (2017). Geopolitan democracy in the Anthropocene. *Political Studies*, 65(4): 983-999.

EEA. (2021, August 08). *Greenhouse gas emissions by aggregated sector*. Retrieved from EEA: https://www.eea.europa.eu/data-and-maps/daviz/ghg-emissions-by-aggregated-sector-5#tab-dashboard-02

Egbue, O., & Long, S. (2012). Barriers to widespread adoption of electric vehicles: An analysis of consumer attitudes and perceptions. *Energy Policy*, 48: 717-729. https://doi.org/10.1016/j.enpol.2012.06.009.

EU The Covenant of Mayors. (2016). *The Covenant of Mayors for Climate and Energy Reporting Guidelines.* Covenant of Mayors & Mayors Adapt Offices, Joint Research Centre of the European Commission.

Fang, K., Heijungs, R., & Snoo, G. R. (2015). Understanding the complementary linkages between environmental footprints and planetary boundaries in a footprint–boundary environmental sustainability assessment framework. *Ecological Economics*, 114: 218-226.

Finkbeiner, M., Inaba, A., Tan, R., Christiansen, K., & Klüppel, H.-J. (2006). The new international standards for life cycle assessment: ISO 14040 and ISO 14044. *The international journal of life cycle assessment* , 11(2), 80-85.

Finney, S. C. (2014). The 'Anthropocene' as a ratified unit in the ICS International Chronostratigraphic Chart: fundamental issues that must be addressed by the Task Group. *Geological Society, London, Special Publications,*, 395(1), 23-28.

Fromm, E. (1981). Primary and secondary process. *Acad. Psychol. Bull.*, 3:29–45.

Fuchs, D., Sahakian, M., Gumbert, T., Giulio, A. D., Maniates, M., Lorek, S., & Graf, A. (2021). *Consumption Corridors: Living a Good Life within Sustainable Limits.* London: Routledge.

Galaz, V., Biermann, F., Crona, B., Loorbach, D., Folke, C., Olsson, P., . . . Reischl., G. (2012). 'Planetary boundaries'—exploring the challenges for global environmental governance. *Current Opinion in Environmental Sustainability*, 4(1): 80-87. doi.org/10.1016/j.cosust.2012.01.006.

Gallup. (2017). *Samtök sveitarfélaga á höfuðborgarsvæðinu og Vegagerðin.* Reykjavik: Gallup.

Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research policy*, 31(8-9), 1257-1274.

Geels, F. W., Sovacool, B. K., Schwanen, T., & Sorrell, S. (2017). The socio-technical dynamics of low-carbon transitions. *Joule*, 1(3), 463-479.

Georgescu-Roegen, N. (1973). *Utility and Value in Economic Thought, in Wiener.* New York: Dictionary of the History of Ideas, vol 4, Charles Scribner & Sons.

Gibbard, P. L., & Walker., M. J. (2014). The term 'Anthropocene'in the context of formal geological classification. *Geological Society, London, Special Publications*, 395(1), 29-37.

Gore, T., & Alestig, M. (2020). *Confronting carbon inequality in the European Union.* 7.: Oxfam International.

Gough, I. (2015). Climate change and sustainable welfare: the centrality of human needs. *Cambridge Journal of Economics*, 39(5), 1191-1214. https://doi.org/10.1093/cje/bev039.

Gough, I. (2017). Recomposing consumption: defining necessities for sustainable and equitable well-being. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 375(2095), 20160379. https://doi.org/10.1098/rsta.2016.0379.

Gough, I. (2020). Defining floors and ceilings: the contribution of human needs theory. *Sustainability: Science, Practice and Policy* , 16(1), 208-219. doi.org/10.1080/15487733.2020.1814033.

Grossmann, K., Connolly, J. J., Dereniowska, M., Mattioli, G., Nitschke, L., Thomas, N., & Varo, A. (2021). From sustainable development to social-ecological justice: Addressing taboos and naturalizations in order to shift perspective. *Environment and Planning E: Nature and Space* , 0(0) 1–23.

Grübler, A. (2003). *Technology and global change.* Cambridge university press.

Guinee, J. B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., . . . Rydberg, T. (2011). Life cycle assessment: past, present, and future. *Environmental Science & Technology*, 45 (1), 90-96 DOI: 10.1021/es101316v.

Gupta, J. (2012). Negotiating challenges and climate change. *Climate Policy*, 12(5): 630-644.

Haberl, H., Wiedenhofer, D., Virág, D., Kalt, G., Plank, B., Brockway, P., Fishman, T., Hausknost, D., Krausmann, F., Leon-Gruchalski, B. and Mayer, A. (2020). A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: synthesizing the insights. *Environmental Research Letters*, 15(6): 065003.

Hancock, P. A., Nourbakhsh, I., & Stewart, J. (2019). On the future of transportation in an era of automated and autonomous vehicles. *Proceedings of the National Academy of the Sciences of the United States of America*, 116(16): 7684-7691. doi.org/10.1073/pnas.1805770115.

Handy, S. L., Boarnet, M. G., Ewing, R., & Killingsworth, R. E. (2002). How the built environment affects physical activity: Views from urban planning. *American Journal of Preventive Medicine*, 23(2), 64-73. https://doi.org/10.1016/S0749-3797(02)00475-0.

Hawkins, T. R., Singh, B., Majeau-Bettez, G., & Strømman, A. H. (2013). Comparative environmental life cycle assessment of conventional and electric vehicles. *Journal of Industrial Ecology 17.1*, 53-64.

Hawkins, T., Gausen, O. M., & Strømman, A. H. (2012). Environmental impacts of hybrid and electric vehicles—a review. *The International Journal of Life Cycle Assessment*, 997–1014.

Heinberg, R. (2010). *Peak everything: waking up to the century of declines.* New Society Publishers.

Heinisch, V., Göransson, L., Erlandsson, R., Hodel, H., Johnsson, F., & Odenberger, M. (2021). Smart electric vehicle charging strategies for sectoral coupling in a city energy system. *Applied Energy*, 288, 116640.

Heinonen, J., Czepkiewicz, M., Árnadóttir, Á., & Ottelin, J. (2021). Drivers of Car Ownership in a Car-Oriented City: A Mixed-Method Study. *Sustainability*, 13(2): 619. doi.org/10.3390/su13020619.

Heinonen, J., Jalas, M., Juntunen, J. K., Ala-Mantila, S., & Junnila, S. (2013). Situated lifestyles: I. How lifestyles change along with the level of urbanization and what the greenhouse gas implications are—a study of Finland. *Environmental Research Letters,*, 8(2), 025003.

Henderson, J. (2020). EVs are not the answer: a mobility justice critique of electric vehicle transitions. *Annals of the American Association of Geographers*, 110.6: 1993-2010.

Hernández-Palacio, F. (2018). *Urban Densification and the Sustainable City in Norway: A Study of Drivers and Barriers.* NTNU: Doctoral theses at NTNU;2018:105. http://hdl.handle.net/11250/2494468.

Hickel, J. (2018). Is it possible to achieve a good life for all within planetary boundaries? *Third World Quarterly*, 40(1): 18-35. doi.org/10.1080/01436597.2018.1535895.

Hickel, J. (2020). What does degrowth mean? A few points of clarification. *Globalizations*, 1-7. doi.org/10.1080/14747731.2020.1812222.

Hickel, J., & Kallis., G. (2020). "Is green growth possible?" . *New political economy*, 25(4): 469-486.

Hill, G., Heidrich, O., Creutzig, F., & Blythe, P. (2019). The role of electric vehicles in near-term mitigation pathways and achieving the UK's carbon budget. *Applied Energy*, 251: 113111 .

Holden, E., Banister, D., Gössling, S., Gilpin, G., & Linnerud, K. (2019). Grand Narratives for sustainable mobility: A conceptual review. *Energy Research and Social Science*, https://doi.org/10.1016/j.erss.2020.101454.

Holden, E., Linnerud, K., & Banister, D. (2013). Sustainable passenger transport: Back to Brundtland. *Transportation Research Part A: Policy and Practice*, 54: 67-77.

Hofstede, G. (1984). The cultural relativity of the quality of life concept. Academy of Management Review, 9 (3); pp. 389–398.

Huchzermeyer, M. (2011). *Cities with 'slums': From informal settlement eradication to a right to the city in Africa.* Cape Town: University of Cape Town Press.

Hughes, T. P., Carpenter, S., Rockström, J., Scheffer, M., & Walker, B. (2013). Multiscale regime shifts and planetary boundaries. *Trends in ecology & evolution*, 28(7), 389-395.

I.Brand-Correa, L., & K.Steinberger, J. (2017). A Framework for Decoupling Human Need Satisfaction From Energy Use. *Ecological Economics*, 141, 43-52. doi.org/10.1016/j.ecolecon.2017.05.019.

Iacono, M., J.Krizek, K., & AhmedEl-Geneidy. (2010). Measuring non-motorized accessibility: issues, alternatives, and execution. *Journal of Transport Geography*, 18(1): 133-140. doi.org/10.1016/j.jtrangeo.2009.02.002.

ICCT. (2021). *Update on government targets for phasing out new sales of internal combustion engine passenger cars.* International Council of Clean Transportation; Sandra Wappelhorst https://theicct.org/sites/default/files/publications/update-govt-targets-ice-phaseouts-jun2021_0.pdf.

IEA. (2019). *The Future of Hydrogen.* https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf: International Energy Agency (IEA).

IEA. (2020). *I Electric Vehicles.* Paris https://www.iea.org/reports/electric-vehicles: IEA.

IEA. (2020). *Tracking Transport 2020.* https://www.iea.org/reports/tracking-transport-2020: Paris.

IEA (2021), Global EV Data Explorer, IEA, Paris https://www.iea.org/articles/global-ev-data-explorer

IEA. (2021). *Global EV Outlook 2021.* International Energy Agency.

IEA. (2021, 08 08). *IEA Electricity*. Retrieved from Share of renewables, low-carbon sources and fossil fuels in power generation, OECD Total 1990-2019: https://www.iea.org/fuels-and-technologies/electricity

International Labour Office. (2012). *Social protection floor for a fair and inclusive globalization.* Geneva: International Labour Office.

International Organization for Standardizaiton (ISO). (2006). *ISO 14040:2006; Environmental management — Life cycle assessment — Principles and framework.* International Organization for Standardizaiton.

IPCC. (2014). *Climate Change 2014: Mitigation of Climate Change - Transport. Working Group III: Mitigation of Climate.* Potsdam: Intergovernmental Panel on Climate Change.

IPCC. (2021). *Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press. In Press.

Ivanova, D., & Wood, R. (2020). The unequal distribution of household carbon. *Global Sustainability*, 3.

Ivanova, D., Barrett, J., Wiedenhofer, D., Macura, B., Callaghan, M., & Creutzig, F. (2020). Quantifying the potential for climate change mitigation of consumption options. *Environmental Research Letters*, 15(9), 093001.

IVL Swedish Environmental Research Institute. (2021). *Zero-emission vehicles and zones in Nordic cities: Promotion, instruments and effects.* IVL Swedish Environmental Research Institute Ltd.; Anders Roth, Jenny von Bahr, Henrik Kloo, Tomas Wisell; https://www.ivl.se/download/18.2f05652c1775c6085c0174/1612249773483/C566.pdf.

Kahneman, D., Diener, E., & Schwarz, N. (1999). *Well-being: Foundations of hedonic psychology.* Russell Sage Foundation.

Kallis, G. (2011). In defence of degrowth. *Ecological Economics*, 70(5), 873-880. doi.org/10.1016/j.ecolecon.2010.12.007.

Kallis, G. (2019). *Limits: Why Malthus was wrong and why environmentalists should care.* Stanford University Press.

Kallis, G., Kerschner, C., & Martinez-Alier, J. (2012). The economics of degrowth. *Ecological Economics*, 84, 172-180. doi.org/10.1016/j.ecolecon.2012.08.017.

Kallis, G., Kostakis, V., Lange, S., Muraca, B., Paulson, S., & Schmelzer, M. (2018). Research on degrowth. *Annual Review of Environment and Resources*, 43: 291-316.

Kaplan, J. O., Krumhardt, K. M., Ellis, E. C., Ruddiman, W. F., Lemmen, C., & Goldewijk., K. K. (2011). Holocene carbon emissions as a result of anthropogenic land cover change. *The Holocene*, 21(5), 775-791. doi.org/10.1177/0959683610386983.

Karaaslan, E., Zhao, Y., & Tatari, O. (2018). Comparative life cycle assessment of sport utility vehicles with different fuel options. *The International Journal of Life Cycle Assessment*, 23(2): 333-347.

Kennedy, C. A., Ibrahim, N., & Hoornweg, D. (2014). Low-carbon infrastructure strategies for cities. *Nature Climate Change*, 4: 343-346.

Kenworthy, J., & Newman, P. (2015). The End of Automobile Dependence: How Cities are Moving Beyond Car-Based Planning. *Island Press, Washington DC*.

Kester, J., Sovacool, B. K., Noel, L., & Rubens, G. Z. (2020). Rethinking the spatiality of Nordic electric vehicles and their popularity in urban environments: Moving beyond the city? *Journal of Transport Geography*, 82, 102557. doi.org/10.1016/j.jtrangeo.2019.102557.

Keyßer, L. T., & Lenzen, M. (2021). 1.5 °C degrowth scenarios suggest the need for new mitigation pathways. *Nature Communications*, 2676. https://doi.org/10.1038/s41467-021-22884-9.

Kiba-Janiak, M., & Witkowski, J. (2019). Sustainable urban mobility plans: How do they work? *Sustainability*, 11(17), 4605.

Ki-moon, B. (2013). *Planning and Design for Sustainable Urban mobility Global Report on Huma Settlements 2013.* UN-HABITAT.

Kobashi, T., Yamagata, Y., Yoshida, T., Chang, S., Mochizuki, Y., Ahl, A., & Aleksejeva, J. (2020). Smart city and ICT infrastructure with vehicle to X applications toward urban decarbonization. *Urban Systems Design,* 289-333. Elsevier.

Koenig, J. G. (1980). Indicators of urban accessibility: theory and application. *Transportation*, 9(2), 145-172.

Kroll, C., & Zipperer, V. (2020). *Sustainable Development and Populism.* 176: 106723. doi.org/10.1016/j.ecolecon.2020.106723: Ecological Economics.

Kubiszewski, I., Costanza, R., Franco, C., Lawn, P., Talberth, J., Jackson, T., & Aylmer, C. (2013). Beyond GDP: Measuring and achieving global genuine progress. *Ecological economics*, 93, 57-68. doi.org/10.1016/j.ecolecon.2013.04.019.

Kumar, R. R., & Alok, K. (2020). Adoption of electric vehicle: A literature review and prospects for sustainability. *Journal of Cleaner Production*, 253: 119911. doi.org/10.1016/j.jclepro.2019.119911.

Kutzbach, M. J. (2009). Motorization in developing countries: Causes, consequences, and effectiveness of. *Journal of Urban Economics*, 65: 154–166. doi.org/10.1016/j.jue.2008.10.002.

Lamb, W. F., & Steinberger, J. K. (2017). Human well-being and climate change mitigation. *Wiley Interdisciplinary Reviews: Climate Change*, 8(6), e485. doi.org/10.1002/wcc.485.

Lamb, W. F., Antal, M., Bohnenberger, K., Brand-Correa, L. I., Müller-Hansen, F., Jakob, M., . . . Sovacool, B. K. (2020). What are the social outcomes of climate policies? A systematic map and review of the ex-post literature. *Environmental Research Letters*, 15(11): 113006.

Lamb, W., Wiedmann, T., Pongratz, J., Andrew, R., Crippa, M., Olivier, J., . . . Pachauri, S. (2021). A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018. *Environmental Research Letters*, 16 073005 .

Lenton, T. M., & Williams, H. T. (2013). On the origin of planetary-scale tipping points. *Trends in Ecology & Evolution*, 28(7), 380-382.

Lewis, S. L. (2012). We must set planetary boundaries wisely. *Nature News*, 485(7399), 417.

Li, F. G., Trutnevyte, E., & Strachan, N. (2015). A review of socio-technical energy transition (STET) models. *Technological Forecasting and Social Change*, 100: 290-305.

Linnér, B.-O., & Selin, H. (2013). The United Nations Conference on Sustainable Development: forty years in the making. *Environment and Planning C: Government and Policy*, 31(6): 971-987.

Liu, R., Dow, L., & Liu, E. (2011). A survey of PEV impacts on electric utilities. *IEEE*, 1-8.

Lorek, S., & Fuchs, D. (2019). The concept of weak and strong sustainable consumption. In *A Research Agenda for Sustainable Consumption Governance.* Edward Elgar Publishing.

Lucas, K., & Jones, P. (2012). Social impacts and equity issues in transport: an introduction. *Journal of Transport Geography*, 21, 1-3 https://doi.org/10.1016/j.jtrangeo.2012.01.032.

Lucas, K., Mattioli, G., Verlinghieri, E., & Guzman, A. (2016). Transport poverty and its adverse social consequences. *Proceedings of the Institution of Civil Engineers - Transport.* , Vol. 169(6). pp. 353-365). Thomas Telford Ltd. https://doi.org/10.1680/jtran.15.00073.

Lutz, M., & Lux, K. (1988). *Humanistic Economics - the New Challenge.* New York: Bootstrap Press.

Markard, J., & Rosenbloom, D. (2020). A tale of two crises: COVID-19 and climate. *Sustainability: Science, Practice and Policy*, 16(1), 53-60.

Marmiroli, B., Messagie, M., Dotelli, G., & Mierlo, J. V. (2018). Electricity Generation in LCA of Electric Vehicles: A Review. *Applied Sciences*.

Marschall, P., & Klingebiel, S. (2019). *Populism: consequences for global sustainable development, Briefing Paper, No. 8/2019.* Bonn. http://dx.doi.org/10.23661/bp8.2019: Deutsches Institut für Entwicklungspolitik (DIE).

Maslow, A. H. (1943). A Theory of Human Motivation. *Psychological Review*, 50(4): 370–396.

Mattioli, G. (2016). Transport needs in a climate-constrained world. A novel framework to reconcile social and environmental sustainability in transport. *Energy Research & Social Science*, 18, 118-128. https://doi.org/10.1016/j.erss.2016.03.025.

Mattioli, G. (2017). "Forced car ownership" in the UK and Germany: socio-spatial patterns and potential economic stress impacts. *Social Inclusion*, 5(4), 147-160. doi.org/10.17645/si.v5i4.1081.

Mattioli, G., Lucas, K., & Marsden, G. (2017). Transport poverty and fuel poverty in the UK: From analogy to comparison. *Transport Policy*, 59: 93-105. doi.org/10.1016/j.tranpol.2017.07.007.

Mattioli, G., Roberts, C., Steinberger, J. K., & Brown, A. (2020). The political economy of car dependence: A systems of provision approach. *Energy Research & Social Science*, 66: 101486.

Max-Neef, M. A. (1991). *Human scale development: conception, application and further reflections.* London: Apex Press.

May, A. D. (2015). Encouraging good practice in the development of Sustainable Urban Mobility Plans. *Case studies on transport policy*, 3(1), 3-11.

McConnell, C. (1981). *Economics. 8th edition.* New York: McGraw Hill.

Middlemiss, L. (2017). A critical analysis of the new politics of fuel poverty in England. *Critical Social Policy*, 37(3), 425-443.

Milovanoff, A., Minet, L., Cheah, L., Posen, I. D., MacLean, H. L., & Balasubramanian, R. (2021). Greenhouse Gas Emission Mitigation Pathways for Urban Passenger Land Transport under Ambitious Climate Targets. *Environmental Science & Technology*, 55(12): 8236–8246 doi.org/10.1021/acs.est.0c06671.

Millward-Hopkins, J., Steinberger, J. K., Rao, N. D., & Oswald, Y. (2020). Providing decent living with minimum energy: A global scenario. *Global Environmental Change*, 65, 102168. https://doi.org/10.1016/J.GLOENVCHA.2020.102168

Ministry for the Environment and Natural Resources . (2020). *Iceland's National Plan.* Reykjavik: Ministry for the Environment and Natural Resources .

Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., & Group, T. P. (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *6*(7).

Molden, D. (2009). Planetary boundaries: The devil is in the detail. *Nature climate change*, 1(910): 116-117.

Moody, J., Farr, E., Papagelis, M., & Keith., D. R. (2021). The value of car ownership and use in the United States. *Nature Sustainability*, 1-6. doi.org/10.1038/s41893-021-00731-5.

Morris, J. M., Dumble, P. L., & Wigan, M. R. (1979). Accessibility indicators for transport planning. *Transportation Research Part A: General*, 13(2): 91-109.

N.Dempsey, C.Brown, & G.Bramley. (2012). The key to sustainable urban development in UK cities? The influence of density on social sustainability. *Progress in Planning*, 77(3): 89-141. doi.org/10.1016/j.progress.2012.01.001.

Neely, J. G., Magit, A. E., Rich, J. T., Voelker, C. C., Wang, E. W., Paniello, R. C., . . . Bradley, J. P. (2010). A practical guide to understanding systematic reviews and meta-analyses. *Otolaryngology--Head and Neck Surgery*, 142(1): 6-14.

Newman, D., Wells, P., Donovan, C., Nieuwenhuis, P., & Davies, H. (2014). Urban, sub-urban or rural: where is the best place for electric vehicles? *International Journal of Automotive Technology and Management*, 14(3-4), 306-323.

Nordelöf, A., Messagie, M., Tillman, A.-M., Söderman, M. L., & Mierlo, J. V. (2014). Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment? *The International Journal of Life Cycle Assessment, 19*(11), 1866–1890.

Norwegian Ministry of Transport and Communications. (2016). *National Transport Plan 2018-2029.* White Paper.

Nussbaum, M., & Sen, A. (1993). *The quality of life.* Clarendon Press.

O'Neill, D. W., Fanning, A. L., Lamb, W. F., & Steinberger, J. K. (2018). A good life for all within planetary boundaries. *Nature sustainability*, 1(2), 88-95.

Olsson, L. (2019). The Role of Electric Vehicles in Reducing Climate Impact: Swedish Public Debate 2010–2018. *The International Journal of Climate Change: Impacts and Responses*, 11 (3): 1-13. doi:10.18848/1835-7156/CGP/v11i03/1-13.

Ortar, N., & Ryghaug, M. (2019). Should all cars be electric by 2025? The electric car debate in Europe. *Sustainability*, 11(7): 1868.

Oswald, Y., Owen, A., & Steinberger, J. K. (2020). Large inequality in international and intranational energy footprints between income groups and across consumption categories. *Nature Energy*, 5(3), 231-239.

Ottelin, J. (2016). *Rebound effects projected onto carbon footprints - Implications for climate change mitigation in the built environment.* Aalto University publication series DOCTORAL DISSERTATIONS, 219/2016.

Ottelin, J., Heinonen, J., & Junnila, S. (2014). Greenhouse gas emissions from flying can offset the gain from reduced driving in dense urban areas. *Journal of Transport Geography*, 41, 1-9. doi.org/10.1016/j.jtrangeo.2014.08.004.

Ottelin, J., Heinonen, J., & Junnila, S. (2017). Rebound effects for reduced car ownership and driving. In *Nordic Experiences of Sustainable Planning* (pp. 263-283). Routledge.

Pawelski, J. O. (2013). Introduction to philosophical approaches to happiness. *The Oxford handbook of happiness*, 247-251.

Páez, A., Scott, D. M., & Morency, C. (2012). Measuring accessibility: positive and normative implementations of various accessibility indicators. *Journal of Transport Geography*, 25: 141-153.

Pedde, S., Kok, K., Onigkeit, J., Brown, C., Holman, I., & Harrison, P. A. (2019). Bridging uncertainty concepts across narratives and simulations in environmental scenarios. *Regional Environmental Change*, 19, pages 655–666.

Pereira, R. H., Schwanen, T., & Banister, D. (2016). Distributive justice and equity in transportation. *Transport Reviews*, 37(2): 170-191. doi.org/10.1080/01441647.2016.1257660.

Pirgmaier, E., & Steinberger., J. K. (2019). Roots, riots, and radical change—a road less travelled for ecological economics. *Sustainability* , 11(7): 2001.

Pomponi, F., Saint, R., A. J., Gharavi, N., & D'Amico, B. (2021). Decoupling density from tallness in analysing the life cycle greenhouse gas emissions of cities. *Urban Sustainability*, 1(1): 1-10.

Rajper, S. Z., & Albrecht, J. (2020). Prospects of electric vehicles in the developing countries: a literature review. *Sustainability*, 12(5): 1906.

Rao, N. D., & Min, J. (2018). Decent living standards: material prerequisites for human wellbeing. *Social indicators research*, 138(1), 225-244.

Rao, N.D., Min, J. & Mastrucci, A. Energy requirements for decent living in India, Brazil and South Africa. *Nat Energy* 4, 1025–1032 (2019). https://doi.org/10.1038/s41560-019-0497-9

Raworth, K. (2012). A safe and just space for humanity: can we live within the doughnut? *Oxfam*.

Raworth, K. (2017). A Doughnut for the Anthropocene: humanity's compass in the 21st century: Supplementary Appendix. *Lancet Planet Health*, 1: e48–49.

Raworth, K. (2017). *Doughnut economics: seven ways to think like a 21st-century economist.* Chelsea Green Publishing.

Raworth, K., Krestyaninova, O., Eriksson, F., Feibusch, L., Sanz, C., Benyus, J., . . . Lipton, J. (2020). *The Amsterdam City Doughnut. A tool for transformative Action.*

2020: Doughnut Economics Action Lab (DEAL); Biomimicry 3.8; Circle Economy; C40.

Richardson, H. W. (1972). Optimality in city size, systems of cities and urban policy: a sceptic's view. *Urban studies*, 9(1): 29-48.

Ritchie, H., & Roser, M. (n.d.). *Urbanization*. Retrieved from Published online at OurWorldInData.org: Retrieved from: 'https://ourworldindata.org/urbanization' [Online Resource]

Robinson, J. B. (1990). Futures under glass: a recipe for people who hate to predict. *Futures*, 22(8): 820-842.

Robinson, J. (2016). Thinking cities through elsewhere: Comparative tactics for a more global urban studies. *Progress in human geography*, 40(1), 3-29

Rockström, J., Gupta, J., Lenton, T. M., Qin, D., Lade, S. J., Abrams, J. F., . . . al., e. (2021). Identifying a Safe and Just Corridor for People and the Planet. *Earth's Future*, 9(4): e2020EF001866.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F., Lambin, E., . . . Nykvist, B. (2009). Planetary boundaries: exploring the safe operating space for humanity. *Ecology and society*, 14(2). http://www.jstor.org/stable/26268316.

Rode, P., Floater, G., Thomopoulos, N., Docherty, J., Schwinger, P., Mahendra, A., & Fang, W. (2014). *Accessibility in Cities: Transport and Urban Form.* NCE Cities Paper 03. LSE Cities. London School of Economics

Ryan, R. M., & Deci., E. L. (2001). On happiness and human potentials: A review of research on hedonic and eudaimonic well-being. *Annual review of psychology*, 52(1): 141-166.

Saunders, F. P. (2015). Planetary boundaries: at the threshold… again: sustainable development ideas and politics. *Environment, development and sustainability*, 17(4): 823-835.

Savy, M., & Burnham, J. (2013). *Freight transport and the modern economy.* Routledge.

Schwanen, T. (2021). Achieving just transitions to low-carbon urban mobility. *Nature Energy*, 1-3.

Sdoukopoulos, A., Pitsiava-Latinopoulou, M., Basbas, S., & Papaioannou, P. (2019). Measuring progress towards transport sustainability through indicators: Analysis and metrics of the main indicator initiatives. *Transportation Research Part D: Transport and Environment*, 67: 316-333 https://doi.org/10.1016/j.trd.2018.11.020.

Seto, K., Dhakal, S., Bigio, A., Blanco, H., Delgado, G., Dewar, D., . . . McMahon, J. (2014). Human settlements, infrastructure and spatial planning. In IPCC, *Climate Change 2014: Mitigation of Climate Change. IPCC Working Group III Contribution to AR5.* Cambridge University Press.

Shafiei, E., Davidsdottir, B., Stefansson, H., Asgeirsson, E. I., Fazeli, R., Gestsson, M. H., & Leaver, J. (2019). Simulation-based appraisal of tax-induced electro-mobility promotion in Iceland and prospects for energy-economic development. *Energy Policy, 133*(110294).

Shafiei, E.; B. Davidsdottir; J. Leaver; H. Stefansson; E. I. Asgeirsson. (2015). Simulation of alternative fuel markets using integrated system dynamics model of energy system. *Procedia Computer Science, 51*, 513-521.

Short, W., & Denholm, P. (2006). Preliminary assessment of plug-in hybrid electric vehicles on wind energy markets. *National Renewable Energy Lab (NREL)*.

Siddique, A., Shahzad, A., JennyLawler, A.Mahmoud, K., Lee, D. S., Bilal, N. A., & Rasool, K. (2021). Unprecedented environmental and energy impacts and challenges of COVID-19 pandemic. *Environmental Research*, 193: 110443. doi.org/10.1016/j.envres.2020.110443.

Simon, D. (2011). Situating slums: Discourse, scale and place, special section, Beyond the return of the "slum. *City*, 15(6): 674–685.

Simon, D. (2016). *Rethinking sustainable cities: Accessible, green and fair.* Policy Press.

Sintov, N. D., Abou-Ghalioum, V., & White, L. V. (2020). The partisan politics of low-carbon transport: Why democrats are more likely to adopt electric vehicles than Republicans in the United States. *Energy Research & Social Science*, 68: 101576.

Smith, A. (1776). *An Inquiry into the Nature and Causes of the Wealth of Nations,.* (reprinted 1976) Campbell, R and A Skinner (eds), Oxford University Press, Oxford.

Sousanis, J. (2011). *World vehicle population tops 1 billion units.* Wards Auto 15.

Spangenberg, J. H. (2014). Institutional change for strong sustainable consumption: sustainable consumption and the degrowth economy. *Sustainability: Science, Practice and Policy*, 10(1): 62-77.

Sperling, Daniel. Three revolutions: Steering automated, shared, and electric vehicles to a better future. *Island Press*, 2018.

Spielmann, M., Haan, P. d., & Scholz, R. W. (2008). Environmental rebound effects of high-speed transport technologies: a case study of climate change rebound effects of a future underground maglev train system. *Journal of Cleaner Production*, 16(13): 1388-1398.

Sovacool, B. K., Hook, A., Martiskainen, M., & Baker, L. (2019). The whole systems energy injustice of four European low-carbon transitions. *Global Environmental Change*, 58, 101958.

Steffen, W. L., Rockström, J., & Costanza, R. (2011). How defining planetary boundaries can transform our approach to growth. *Solutions: For A Sustainable & Desirable Future*.

Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., & Ludwig, C. (2015). The trajectory of the Anthropocene: the great acceleration. *The Anthropocene Review*, 2(1), 81-98. https://doi.org/10.1177/2053019614564785.

Steffen, W., Crutzen, P. J., & McNeill, J. R. (2016). The Anthropocene: Are humans now overwhelming the great forces of nature? *The New World History*, 440-459.

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., & al, R. B. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science*, 347(6223).

Steffen, W., Sanderson, R., Tyson, P., Jäger, J., Matson, P., III, B. M., . . . Wasson, R. (2004). Global change and the earth system: a planet under pressure. *pringer Science & Business Media*.

Tahmasbi, B., Mansourianfar, M. H., Haghshenas, H., & Kim, I. (2019). Multimodal accessibility-based equity assessment of urban public facilities distribution. *Sustainable Cities and Society*, 9: 101633. doi.org/10.1016/j.scs.2019.101633.

Tay, L. and Diener, E. (2011). Needs and subjective well-being around the world. Journal of Personality and Social Psychology, 101(2); pp. 354–365.

Tight, M., Rajé, F., & Timms, P. (2016). Car-Free Urban Areas: A Radical Solution to the Last Mile Problem or a Step Too Far? *Built Environment*, 42(4):. 603-616(14). doi.org/10.2148/benv.42.4.603.

Tollefson, J. (2021, January 15). COVID curbed carbon emissions in 2020 — but not by much. *Nature.*

Trigg, Andrew B. "Deriving the Engel curve: Pierre Bourdieu and the social critique of Maslow's hierarchy of needs." *Review of Social Economy* 62.3 (2004): 393-406.

UN General Assembly. (1948). *Universal declaration of human rights.* 302.2: 14-25: UN General Assembly.

UNEP, UNEP DTU Partnership. (2020). *Emissions Gap Report 2020.* UNEP, UNEP DTU Partnership.

UN-Habitat. (2019). *Addressing Systemic Barriers for Achieving Sustainable Urbanization in Emerging Economies: Learnings from the 19 Cities of the Global Future Cities Programme.* Nairobi: United Nations Human Settlements Programme (UN-Habitat).

United Nations. (2015). *Transforming Our World: The 2030 Agenda for Sustainable Development.* United Nations.

Urry, J. (2004). The 'System' of Automobility. *Theory, Culture & Society*, 21(4-5): 25–39. doi:10.1177/0263276404046059 .

Van Vuuren, D. P., Kok, M. T., Girod, B., Lucas, P. L., & Vries, B. d. (2012). Scenarios in global environmental assessments: key characteristics and lessons for future use.

Global Environmental Change, 22(4): 884-895. doi.org/10.1016/j.gloenvcha.2012.06.001.

Vergragt, P. J., & Quis, J. (2011). Backcasting for sustainability: Introduction to the special issue. *Technological Forecasting and Social Change*, 78(5): 747-755. doi.org/10.1016/j.techfore.2011.03.010.

Voinov, A., & Bousquet, F. (2010). Modelling with stakeholders. *Environmental modelling & software*, 25(11), 1268-1281. doi.org/10.1016/j.envsoft.2010.03.007.

Waddell, J., Rylander, M., Maitra, A., & Taylor, J. A. (2011). Impact of plug in electric vehicles on Manitoba Hydro's distribution system. *IEEE*.

Wangsness, P. Brevik, & A. H. Halse. (2021). The impact of electric vehicle density on local grid costs: Empirical evidence from Norway. *The Energy Journal*, 42.5.

Waterman, A. (1993). Two conceptions of happiness: contrasts of personal expressiveness. *J. Pers. Soc. Psychol.*, 64:678–91.

Whelan, G. (2007). Modelling car ownership in Great Britain. *Transportation Research Part A: Policy and Practice*, 41(3): 205-219. doi.org/10.1016/j.tra.2006.09.013.

Wiedenhofer, D., Virág, D., Kalt, G., Plank, B., Streeck, J., Pichler, M., Mayer, A., Krausmann, F., Brockway, P., Schaffartzik, A., Fishman, T., Hausknost, D., Leon-Gruchalski, B., Sousa, T., Creutzig, F., & Haberl, H. (2020). A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part I: Bibliometric and conceptual mapping. *Environmental Research Letters*, 15(6): 063002. Institute of Physics Publishing. https://doi.org/10.1088/1748-9326/ab8429

Wiedmann, T., Lenzen, M., Keyßer, L. T., & Steinberger, J. K. (2020). Scientists' warning on affluence. Nature communications. *Nature communications*, 11(1), 1-10.

Wilkinson, I. P., Poirier, C., Head, M. J., Sayer, C. D., & Tibby, J. (2014). Microbiotic signatures of the Anthropocene in marginal marine and freshwater palaeoenvironments. *Geological Society, London, Special Publications*, 395(1): 185-219. doi.org/10.1144/SP395.14.

Wilkinson, R. G., & Pickett, K. E. (2009). Income inequality and social dysfunction. *Annual review of sociology*, 35, 493-511 https://doi.org/10.1146/annurev-soc-070308-115926.

Willett, W. R. (2019). Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet*, 393(10170), 447-492.

WMO. (2021). *WMO Global Update to Decadal Clmate Update.* World Meteorological Organization.

Woldeamanuel, M. G., Cyganski, R., Schulz, A., & Justen, A. (2009). Variation of households' car ownership across time: application of a panel data model. *Transportation*, 36: 371–387.

World Bank. (2008). *World development report 2009: Reshaping economic geography.* The World Bank.

World Commission on Environment and Development, a. G. (1987). *Presentation of the Report of the World Commission on Environment and Development to the Commission of the European Communities, the EC and EFTA Countries... 5 May 1987.* World Commission on Environment and Development.

Zalasiewicz, J., Waters, C., Williams, M., Barnosky, A., Cearreta, A., Crutzen, P., . . . Haff, P. (2015). When did the Anthropocene begin? A mid-twentieth century boundary level is stratigraphically optimal. *Quaternary International*, 383: 196-203. doi.org/10.1016/j.quaint.2014.11.045.

Zhang, H.-B., Dai, H.-C., Lai, H.-X., & Wang, W.-T. (2017). U.S. withdrawal from the Paris Agreement: Reasons, impacts, and China's response. *Advances in Climate Change Research*, 8(4): 220-225.

Zhang, R., & Zhang, J. (2021). Long-term pathways to deep decarbonization of the transport sector in the post-COVID world. *Transport Policy*, 110: 28-36. doi.org/10.1016/j.tranpol.2021.05.018.

Zumsteg, J. M., Cooper, J. S., & Noon, M. S. (2012). Systematic Review Checklist: A Standardized Technique for Assessing and Reporting Reviews of Life Cycle Assessment Data. *Journal of Industrial Ecology*, 16: S12-S21.

Papers 1-4

The articles are listed in the order that they appear.

Paper I (P1)

Dillman, K. J., Árnadóttir, Á., Heinonen, J., Czepkiewicz, M., & Davíðsdóttir, B. (2020). Review and meta-analysis of EVs: Embodied emissions and environmental breakeven. *Sustainability*, 12(22), 9390.

DOI: 10.3390/su12229390

> Corrections to *Paper I (P1)*
>
> **Dillman, K. J.,** Árnadóttir, Á., Heinonen, J., Czepkiewicz, M., & Davíðsdóttir, B. (2021). Correction: Dillman et al. Review and Meta-Analysis of EVs: Embodied Emissions and Environmental Breakeven. *Sustainability*, 13(9), 5195.
>
> DOI: 10.3390/su13095195

Paper II (P2)

Dillman, K.J., Czepkiewicz, M., Heinonen, J., Fazeli, R., Árnadóttir, Á., Davíðsdóttir, B., & Shafiei, E. (2021d). Decarbonization scenarios for Reykjavik's passenger transport: The combined effects of behavioural changes and technological developments. *Sustainable Cities and Society,* 65, 102614.

DOI: 10.1016/j.scs.2020.102614

Paper III (P3)

Dillman, K. J., Fazeli, R., Shafiei, E., Jónsson, J. Ö. G., Haraldsson, H. V., & Davíðsdóttir, B. (2021a). Spatiotemporal analysis of the impact of electric vehicle integration on Reykjavik's electrical system at the city and distribution system level. *Utilities Policy*, 68, 101145.

DOI: 10.1016/j.jup.2020.101145

Paper IV (P4)

Dillman, K.J., Czepkiewicz, M., Heinonen, J., & Davíðsdóttir, B. (2021c). A Safe and Just Space for Urban Mobility - A Framework for Sector-Based Sustainable Consumption Corridor Development. *Global Sustainability*, 1-42.

DOI: 10.1017/sus.2021.28