Studies on societal metabolism from households to the global economy

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Ph.D. Dissertation
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A l’Aina,

i a totes les que vindran

Abstract

Achieving sustainability is a wicked problem requiring the consideration of many non-equivalent and non-comparable variables and fields simultaneously, not only climate change mitigation and adaptation, as it is framed in many cases. These include other issues, such as resource scarcity (peak oil, phosphorous scarcity, etc.), pollution, biodiversity loss, deforestation, eutrophication, hunger and poverty. To tackle this polycrisis, we must understand the metabolism of socio-ecological systems beyond a mere accounting of inputs and outputs, including the internal configuration of society and the role and entanglements of resources. This way, we can explore the option space for deep transformations. Functional and structural elements in social-ecological systems are organised hierarchically and in networks, just as cells constitute organs connected in bodies.

In this thesis, I explore some overlooked and critical concepts transforming the economics paradigm: societal metabolism, networks, biophysical limits, and incommensurable trade-offs. The objective is to contribute to the holistic understanding and quantitative analysis of socio-ecological systems. More specifically, the inclusion of time use and its nexus to energy and power capacity are analysed at different scales. To do so, I connect a theoretical background derived from bioeconomics and practice theory and use methods from ecological economics (Multi-Scale Integrated Assessment of Societal and Ecosystem Metabolism – MuSIASEM and its tool, End-Use Matrix) and industrial ecology (Environmentally Extended Input-Output Tables - EEIO). The case studies explore various sectors at different scales, mainly from the perspective of European countries, including the residential sector, the automotive industry, and global production networks. Therefore, this thesis aims to break down the silos between disciplines and sectors.

The first case study assesses household metabolism by reviewing key factors and possible strategies for its sustainability across many dimensions. We analyse the concept of home as an institution and its function in the economy, the form and materiality of dwellings, and how these elements shape, relate to, and limit each other. More specifically, I analyse the role of the funds: human activity (i.e., time use), power capacity (i.e., devices and appliances), and floor area (i.e., buildings). The study provides a list of strategies to improve its sustainability, considering the effects in different dimensions. This study is a first step towards better models and a holistic quantification of household metabolism.

From the household to the global economy level, human time is a key and overlooked limit. Working time at the global level is a zero-sum game, where some countries have net imports and others have net exports of embodied labor due to trade. The second case study analyses the international exchanges of embodied working time for the EU, the US, and China in 2011 and how these affect national metabolisms. Global

production networks are shaped by the international division of labour, functional specialisation, and unequal exchange. In this case, half of the EU and US's consumption of embodied working time is foreign. This imported time has implications for the activities carried out in their national economies (towards tertiarization) and in fewer working hours per worker.

These hierarchical relations and functional specialisation in the international division of labour can also be found within individual economic sectors The third case study exposes the different characteristics and roles of the automotive industry in a selection of eight European countries in 2018 through a multidimensional and multilevel quantitative assessment. This is an application of the End-use Matrix to a specific industrial activity that shows how the variety of functions within the same sector are linked to different levels of direct energy use and economic and environmental impacts.

Resum

Assolir la sostenibilitat és un problema pervers que requereix la consideració de moltes variables i camps no equivalents i no comparables simultàniament, no només la mitigació i l'adaptació al canvi climàtic, com s'emmarca en molts casos. Aquests inclouen altres qüestions, com l'escassetat de recursos (pic del petroli, escassetat de fòsfor, etc.), la contaminació, la pèrdua de biodiversitat, la desforestació, l'eutrofització, la fam i la pobresa. Per fer front a aquesta policrisi, hem d'entendre el metabolisme dels sistemes socioecològics més enllà d'una mera explicació dels inputs i outputs, incloses la configuració interna de la societat i el paper i el nexe dels recursos. D'aquesta manera, podem explorar l'espai d'opcions per a transformacions profundes. Els elements funcionals i estructurals dels sistemes socioecològics s'organitzen jeràrquicament i en xarxes, de la mateixa manera que les cèl·lules constitueixen òrgans connectats en cossos.

En aquesta tesi, exploro alguns conceptes crítics i passats per alt que transformen el paradigma econòmic: metabolisme societal, xarxes, límits biofísics i solucions de compromís. L'objectiu és contribuir a la comprensió holística i l'anàlisi quantitativa dels sistemes socioecològics. Més concretament, la inclusió de l'ús del temps i el seu nexe amb l'energia i la capacitat de potència s'analitzen a diferents escales. Per fer-ho, connecto una base teòrica de bioeconomia i teoria de les pràctiques socials i faig servir mètodes de l'economia ecològica (Multi-Scale Integrated Assessment of Societal and Ecosystem Metabolism - MuSIASEM i la seva eina, End-Use Matrix) i l'ecologia industrial (Taules Input-Output amb extensions ambientals - EEIO). Els estudis de cas exploren diversos sectors a diferents escales, principalment des de la perspectiva dels països europeus, que inclouen el sector residencial, la indústria de l'automoció i les xarxes de producció mundials. Per tant, aquesta tesi pretén construir ponts entre disciplines i sectors.

El primer cas d'estudi avalua el metabolisme de les llars revisant factors clau i possibles estratègies per a la seva sostenibilitat en moltes dimensions. Analitzem el concepte de nucli familiar o de convivència com a institució i la seva funció a l'economia, la forma i la materialitat dels habitatges, i com aquests elements es configuren, es relacionen i es limiten entre si. Més específicament, analitzo el paper dels fons: activitat humana (l'ús del temps), la capacitat d'energia (dispositius i aparells) i l'àrea (edificis). L'estudi ofereix una llista d'estratègies per millorar la seva sostenibilitat, considerant els efectes en diferents dimensions. Aquest estudi és un primer pas cap a millors models i una quantificació holística del metabolisme domèstic.

Des de la llar fins a l'economia global, el temps humà és un límit clau i passat per alt. El temps de treball a nivell mundial és un joc de suma zero, on alguns països tenen importacions netes i altres tenen exportacions netes. El segon cas d'estudi analitza els intercanvis de temps de treball en el comerç internacional a la UE, els EUA i la Xina el

2011 i com aquests afecten els metabolismes nacionals. Les xarxes globals de producció estan conformades per la divisió internacional del treball, l'especialització funcional i l'intercanvi desigual. En aquest cas, la meitat del consum de temps de treball incorporat de la UE i els EUA és estranger. Aquest temps importat té implicacions a les activitats que es duen a terme a les seves economies nacionals (cap a serveis) i en menys hores de treball per treballador.

Aquestes relacions jeràrquiques i l'especialització funcional en la divisió internacional del treball també es poden trobar dins d'un sector econòmic determinat. El tercer cas d'estudi exposa les diferents característiques i rols de la indústria de l'automoció en una selecció de vuit països europeus el 2018 mitjançant una avaluació quantitativa multidimensional i multinivell. Es tracta d'una aplicació de la matriu d'usos finals a una activitat industrial concreta que mostra i com la varietat de funcions dins d'un mateix sector està vinculada a diferents nivells d'ús directe d'energia i impactes econòmics i ambientals.

Resumen

Lograr la sostenibilidad es un problema perverso que requiere la consideración de muchas variables y campos no equivalentes y no comparables simultáneamente, no solo la mitigación y adaptación al cambio climático, como se enmarca en muchos casos. Estos incluyen otros problemas, como la escasez de recursos (pico del petróleo, escasez de fósforo, etc.), la contaminación, la pérdida de biodiversidad, la deforestación, la eutrofización, el hambre y la pobreza. Para abordar esta policrisis, debemos comprender el metabolismo de los sistemas socioecológicos más allá de un mero recuento de flujos de entrada y salida, incluida la configuración interna de la sociedad y el papel y el nexo de los recursos. De esta manera, podemos explorar el espacio de opciones para transformaciones profundas. Los elementos funcionales y estructurales en los sistemas socio-ecológicos están organizados jerárquicamente y en redes, así como las células constituyen órganos conectados en los cuerpos.

En esta tesis, exploro algunos conceptos críticos y pasados por alto que transforman el paradigma económico: metabolismo social, redes, límites biofísicos y soluciones de compromiso. El objetivo es contribuir a la comprensión holística y al análisis cuantitativo de los sistemas socioecológicos. Más específicamente, la inclusión del uso del tiempo y su nexo con la energía y la capacidad de potencia se analizan a diferentes escalas. Para hacerlo, conecto un trasfondo teórico derivado de la bioeconomía y la teoría de la práctica y uso métodos de la economía ecológica (Evaluación integrada multiescala del metabolismo social y del ecosistema - MuSIASEM y su herramienta, Matriz de usos finales) y la ecología industrial (Tablas input-output con extensiones ambienteles - EEIO). Los casos de estudio exploran varios sectores a diferentes escalas, principalmente desde la perspectiva de los países europeos, incluido el sector residencial, la industria automotriz y las redes de producción global. Por lo tanto, esta tesis pretende romper los silos entre disciplinas y sectores.

El primer caso de estudio evalúa el metabolismo del hogar mediante la revisión de factores clave y posibles estrategias para su sostenibilidad en muchas dimensiones. Analizamos el concepto de hogar como institución y su función en la economía, la forma y materialidad de las viviendas, y cómo estos elementos se configuran, relacionan y limitan entre sí. Más específicamente, analizo el papel de la actividad humana de los fondos (el uso del tiempo), la capacidad de energía (dispositivos y electrodomésticos) y la superficie (edificios). El estudio proporciona una lista de estrategias para mejorar su sostenibilidad, considerando los efectos en diferentes dimensiones. Este estudio es un primer paso hacia mejores modelos y una cuantificación holística del metabolismo doméstico.

Desde el hogar hasta el nivel de la economía global, el tiempo humano es un límite clave y generalmente pasado por alto. El tiempo de trabajo a nivel global es un juego de suma cero, donde algunos países tienen importaciones netas y otros tienen

exportaciones netas. El segundo caso de estudio analiza los intercambios internacionales de horas de trabajo incorporadas para la UE, los EE.UU. y China en 2011 y cómo estos afectan los metabolismos nacionales. Las redes globales de producción están formadas por la división internacional del trabajo, la especialización funcional y el intercambio desigual. En este caso, la mitad del consumo de tiempo de trabajo incorporado de la UE y los EE.UU. es extranjero. Este tiempo importado tiene implicaciones en las actividades que realizan en sus economías nacionales (hacia los servicios) y en menos horas de trabajo por trabajador.

Estas relaciones jerárquicas y de especialización funcional en la división internacional del trabajo también se pueden encontrar dentro de un mismo sector económico. El tercer caso de estudio expone las diferentes características y roles de la industria automotriz en una selección de ocho países europeos en 2018 a través de una evaluación cuantitativa multidimensional y multinivel. Esta es una aplicación de la Matriz de usos finales a una actividad industrial específica que muestra cómo la variedad de funciones dentro de un mismo sector está vinculada a diferentes niveles de uso directo de energía e impactos económicos y ambientales.

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que en sortim almenys més fortes i sàvies. A Clara, quien ha estado presente pese la distancia. No voldria allargar-me molt però no voldria deixar de mencionar també (en ordre alfabètic) a l'Aina, l'Andrea, en Fran, la Fran, la Oihane, la Laura, en Marc, la Míriam, la Núria, en Roberto, la Teresa, en Xavi, a la resta d'amics i col·legues de la delegació d'estudiants de l'ETSEIB, de la universitat, del màster, i del futbol.

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Acronyms

EJP – Economic Job Productivity
EMR – Energy Metabolic Rate
ET – Energy Throughput
HA – Human Activity
GHG – Greenhouse Gases
GHGER – Greenhouse Gas Emission Rate
GVA – Gross Value Added
MVI – Motor vehicles industry
MuSIASEM – Multi-Scale Integrated Assessment of Societal and Environmental Metabolism
PC – Power Capacity
VPR – Vehicle Production Rate

Preface

Some years ago, I was working as a mechanical engineer in an electric motor repair shop. Most of my working day was spent was measuring and drawing all kinds of parts. I would go from side to side of the repair shop with a vernier caliper always in the pocket ready to measure any diameter. My duties also involved being the supervisor of more precise measuring instruments that could go to the nanometer for ensuring the accuracy of the most precise machine tools.

After this job, I decided to do a master on sustainability at UAB. Sustainability is a great challenge to which we were not really trained in the engineering degree, even though here and there some professors would talk to us about it out of the syllabus. That master's took me away from the paradigm of my previous job where we can predict and control the functioning of machines and we should search of ever more exact measurements. From that point on, people and social issues entered into the picture and, in fact, vertebrated the challenges. People do appear very seldom in engineering and when they do it is in the form of money: how much they are willing to pay. However, uncertainty and compromise solutions are some of the key ideas in engineering. For example, one of the basic trade-offs that we learn in project management or manufacturing is that we cannot combine speed, quality and a low cost.

The master thesis on urban metabolism of Barcelona, under the supervision of Maddalena Ripa and Mario Giampietro served as my introduction to the IASTE group. This PhD dissertation stems from my participation in European projects (Euforie and Magic-NEXUS) and a project with the Swedish Environmental Agency in 2019-2020. This project aimed to explore the current state of the Swedish economy and envision possible pathways to sustainability towards 2050 with Quantitative Storytelling and the participation of their climate change, circular economy, and biodiversity teams.

This started with a broad overview of the national metabolism of Sweden and some of its subsectors. It made me get to know the existing data for that country and explore literature from different fields. I had the privilege to expand my engineering (and a bit of architecture) background by incorporating some sociology, geography, economics, and architecture in my Ph.D. Through what become a preliminary overview of the societal metabolism of Sweden and some of its sectors, I could find questions that could be extended and further explored more freely after the project ended. Some of them are shown in the case studies in this dissertation. In this sense, this is not a traditional dissertation, whose research questions have been set at the beginning of the journey. Its objectives have evolved through time and learning by doing.

I have been part of the Integrated Assessment: Sociology, Technology and the Environment (IASTE) research group led by Mario Giampietro at ICTA-UAB (Institut de Ciència i Tecnologia Ambientals, Universitat Autònoma de Barcelona). The research topics I touched on mainly covered aspects or sectors complementing and building up those of colleagues within the Multi-Scale Integrated Assessment of Societal and Ecosystem Metabolism (MuSIASEM). Moreover, being part of ICTA, I could enjoy many seminars related to a vast array of fields related to environmental sciences, from oceans to environmental justice.

I did a research stay in spring 2022 at CML-Leiden University with Tomer Fishman and Paul Behrens. This was a very fruitful project where I could collaborate with people in other disciplines and with different backgrounds which nurture each others' perspectives. I could implement a metabolic/bioeconomics/social practice framework to industrial ecology tools. Also, I could attend a summer school related to the LOCOMOTION h2020 project and a short visit to Universidad de Valladolid in spring 2023, where I could learn about one of the most complete Integrated Assessment Model and system dynamics. Therefore, I could go even beyond the vast breadth of fields where MuSIASEM is rooted. These experiences have broadened my perspective and provided a contextual understanding of the work I was doing at UAB.

This dissertation is only the tip (or many tips) of the iceberg of the work done these years. The chapters reflect only some of the most interesting outcomes I've been the lead author of. The broad array of topics and questions in this dissertation is explained by other work not included here that connects the dots and even explores other fields or sectors. Some of this work has been published or has been submitted for publication: energy systems (Di Felice et al., n.d.), forestry industries (Velasco-Fernández et al., 2019), national end-use matrixes (Velasco-Fernández et al., 2020b) and time use (Manfroni et al., 2021). Much of the work that I've done these years is stored in my hard drives and cloud. Certain projects hold potential for publication, while others may not be deemed particularly noteworthy for the research community. Such circumstances are inherent to the research process and should be acknowledged. Regardless, this entire journey has granted me invaluable experiences and knowledge.

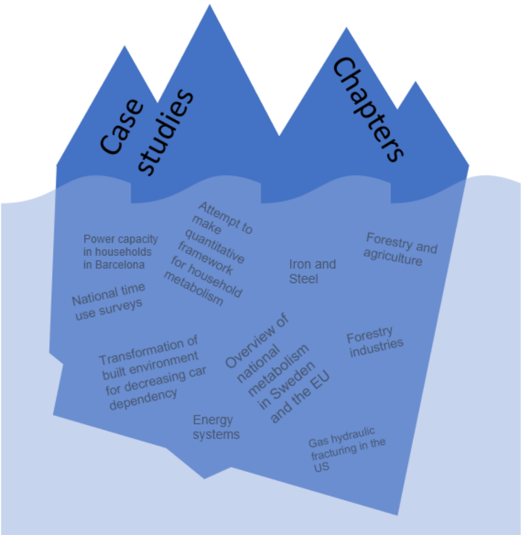


Figure 1 The iceberg has a tip of dissertation chapters over water and invisible work below water that is published as a co-author in peer review journals or not published.

This dissertation was done in the context of a pandemic with a lockdown and other measures limiting in-person activities which was followed by a cyberattack at UAB. This limited in-person conferences, meetings, seminars, and informal conversations but was also an in-practice example of how post-normal science works in shorter-term, with also large doses of uncertainty but a more immediate perceived urgency compared to the sustainability challenge.

The sustainability challenge

Societies have always faced biophysical limits, depletion of resources and degradation of the environment from human activity. Now, this situation has been taken to another level with a metabolism powered and dependent on fossil fuels. While defining the exact carrying capacity of ecosystems and resource availability is an unattainable goal, we know that limits exist and have been surpassed.

Some of these limits refer to the state of the environment as a sink. Climate change impacts and GHG emissions have taken the spotlight, but others at different scales are also impacting the ecosphere: eutrophication, pollution, etc. On the other hand, Earth as a source is limited and is showing an increasing scarcity of the raw materials essential to the current economy, such as fossil fuels (Hubbert, 1971, 1949; Laherrère et al., 2022; Tverberg, 2012), uranium (Dittmar, 2013), nutrients (Cordell and White, 2011), minerals for energy transition (Calvo and Valero, 2022; European Commission, 2020; Graedel et al., 2015; Valero et al., 2018) or even bulk abundant materials such as sand (Torres et al., 2021). There is an interconnected environmental poly-crisis affecting the state of ecosystems in a plethora of ways, from the local to the global scale. The planetary boundaries concept includes some of these global critical limits (Rockström et al., 2009). The overall impact is larger than the sum of each part, and these impacts are interconnected (Zscheischler et al., 2018). Moreover, the damage could take us to irreversible states when we reach the tipping points (Lenton, 2011; Lenton et al., 2008).

Both pressures on the sinks and depletion of high-quality and easy-to-extract sources can trigger instability in the economic system. Moreover, the overburden of sinks also affects the productive capacity of sources. For example, climate change caused by the growing concentration of GHG in the atmosphere affects biomass extraction through agriculture and forestry due to the higher temperatures and drought, with less frequent and more destructive rainfall.

However, sustainability is not only about the state of the ecosphere. It requires the fulfillment of needs of society, now and in the future. We can see this in the Brundtland report, one of the most cited references for the definition of sustainable development: "*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). This definition is very general. Sustainable development is a very ambiguous term (Dixon and Fallon, 1989; Naredo, 2015). This elusiveness is inherent to many great concepts, like democracy or justice (Daly, 1997a). Instead, other authors consider this ambiguity an obstacle to changing the status quo (Naredo, 2022, 2010). Some actors use the term only cosmetically or rhetorically, while they do not take sufficient action for sustainability. Despite the controversy of this specific term, the ambiguity can generate consensus. What I want to point out here is the general agreement on the centrality of social and economic sustainability, which is shown in conceptualizations such as sustainable development, other succeeding mainstream concepts like the Sustainable Development Goals (SDGs) and other more radical views such as degrowth.

The concept of Doughnut economics, coined by Kate Raworth, extends the logic of the planetary boundaries and puts together some social and environmental thresholds (Raworth, 2017). Within this framework, Fanning et al. (2015) have shown how countries fulfilling social criteria surpass many of the environmental limits from a consumption-based perspective. The economy is damaging the environment while it is fulfilling better or worse human needs (and wants) for a part of humanity. The current development patterns are already overshooting resource use and are not universalisable (Arto et al., 2016; Müller et al., 2013; Wiedenhofer et al., 2022). What is worse, even most countries that do not fulfil any social criteria are surpassing at least one of the seven boundaries.

Therefore, part of the challenge is to secure a level of economic activity with two objectives in mind. We need to fulfil immediate needs in the short-term and in the longer term by building (for those who lack them) or transforming (for those who already have high levels but are unsustainable) the structures for enabling a more sustainable metabolism. A business-as-usual strategy might be viable in the short term to fulfill needs, while it overloads the ecosphere and depletes resources, making it unfeasible mid-term. As we would say in Spanish: "*pan para hoy, hambre para mañana*". All economic activity has an impact. Our economy is damaging the environment, while the correct functioning of natural processes determines the viability of the economy. What we need is to find a balance. A radical conservationist strategy that aims to keep or restore all ecosystems and natural cycles in a "natural" condition would be terrible for the state of provisioning systems and human wellbeing.

The question here is: Can we do things differently so we can still fulfil human needs while decreasing impacts? The open-ended concept of sustainability is concretised in many policy proposals in practice within different paradigms: green growth, degrowth, Green New Deal, etc. These are based on opinions on the constraints and drivers of transformation and prosperity. The debate of whether and how we can fulfil welfare with fewer resources and impacts is concretized in proposals such as technical innovation, decoupling, taxes, or sufficiency measures. To provide answers to that, we need to better understand the current and possible socio-economic systems with a broad perspective in order to manage as much as possible the great complexity, with its possible trade-offs and side-effects of policy.

The final objective of sustainability is not merely to reach a certain emissions target by 2050, but to transform the economy in a way that keeps running while respecting environmental and social limits. To achieve a long-term reproducible economy, we must not take more than the rate of renewable resources that the Earth can provide, which decreases with the accumulation of impacts. And we must limit the need for resources (more importantly for raw non-renewable ones) to guarantee the provisioning of inflows for the smooth functioning of the economy. At the same time, we should adapt to the climate change impacts and other types of degradation of the environment. This entails a change in the organisation and structures of society to guarantee its long-term viability.

Social changes are required not only because they allow for deeper transformations of the system, but also because there are social issues to solve.

As we can see, the challenge is enormous. While there is increasing awareness, the solutions have shown limited effectiveness so far. Many COPs have been held with some attempts to reach global agreements and set national targets. However, the outcomes are doubtful: GHG emissions and other environmental impacts still grow, and resource scarcity increasingly threatens the economy. The anthroposphere has increased its size and metabolism to maintain and make it function (Herrington, 2021; Krausmann et al., 2017; Smil, 2019; Steffen et al., 2015). Part of this irresolution is due to the current positivist paradigm of science, which aims to quantify problems and search for optimums one issue at the time. It does not acknowledge the complexity and uncertainty of social issues, the different perspective of actors, the interaction of many dimensions in complex systems, the connections between sectors, etc. All of this makes that there are no silver bullets to tackle the sustainability crisis. We need a different way to make science and policy.

This introduction may seem very general and evident to many of the readers. Here, I aimed to describe in general terms the polycrisis that humanity is facing, because in many cases it is merely merely reduced to climate change. In fact, it is not only related to the environment and includes social aspects. Of course, a single person cannot analyze and offer solutions for all of this, but it is necessary to acknowledge the magnitude of the challenge. The focus of this dissertation is to analyze some key elements of social organization and anthroposphere, from households to the global economy, with a metabolic perspective.

The more specific theoretical framing or pre-analytic assumptions are detailed in the following introductory sections. In the rest of the introduction, I explain the scientific context that is key for understanding the barriers to interdisciplinary analysis, the more detailed definition of sustainability within ecological economics, elements of practice theory that help us understand how practice, culture and infrastructure are related, and the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) where this dissertation is framed.

Research questions

The sustainability challenge combines the certainties and urgencies of a changing climate, other environmental degradation and resource depletion, with the uncertainties of their exact when and how, and the political challenges of societal transformation. For this reason, a holistic bird's eye overview of socio-ecological systems becomes essential. A broad coverage of topics, sectors and dimensions is required for a well-founded decision-making, and to understand the synergies, trade-offs and limits to economic activity.

The main objective of this dissertation is to explore the metabolism of modern societies and contribute to the generation of alternative quantitative assessments at different scales and dimensions, avoiding the pitfalls of reductionism. There is a special focus on the time-energy nexus, which is key for explaining social organization and for proposing alternatives that generate fewer impacts to the environment. In this sense, the inclusion of time use variables in the MuSIASEM accounting is a distinctive trait in respect to most sustainability assessments. I analyze how time and energy shape and are shaped by social practices within households, specific sectors and the international division of labor. I also analyze how functions are distributed within sectors, countries and households, and the effects of this distribution on metabolic patterns.

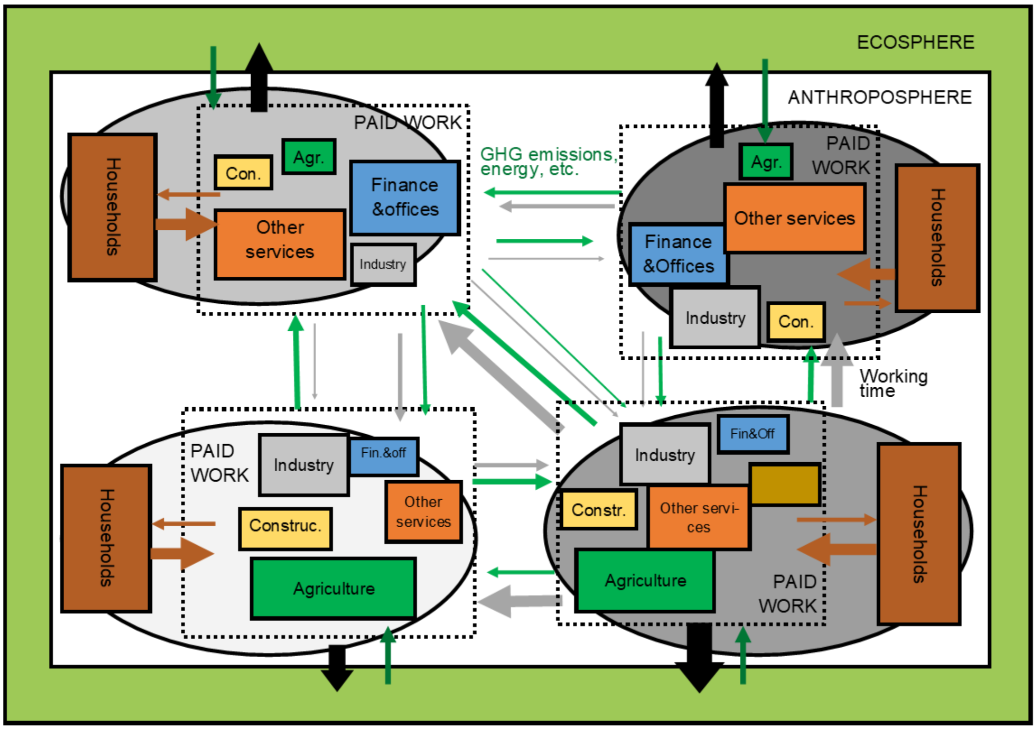


Figure 2 Representation of socio-ecological systems with 4 regions in a globalized economy, with a non-exhaustive set of sectors within paid work.

To do so, we must better understand how material and functional elements are related to each other in socio-ecological systems. In this dissertation, I mainly analyse the organisation of society: their institutions, functions and linkages. One general representation of some main elements in play in socio-ecological systems in a globalized world is shown in Figure 2. There, we can see households interacting with paid work, which is divided in sectors which at lower levels have specific structural elements carrying out functions and producing outputs: machinery, land use, etc. Some of these structural elements are long-lived and generate lock-ins in the system, limiting deep transformation. Paid work in different countries interacts via global markets. These international links go beyond these market interactions of goods and services. Different social-ecological systems interact at the global level also by tourism, seasonal workers or migrants, or by sharing global commons such as the oceans or the atmosphere. Each country, sector, and specific lower-level structure interacts with the ecosphere. These elements, their relationships and other theoretical background will be further explained in the following introductory chapters, but this figure helps putting a first general context to the case studies that I introduce here.

One of the key aspects of sustainability is analyzing the current social organization and exploring whether alternative configurations could require a lower metabolism. This means still providing needs to people with a functioning economy while decreasing the impacts to the environment. When we talk about a functioning economy, we refer to the viability of socio-ecological systems, which defines sustainability together with desirability and environmental feasibility.

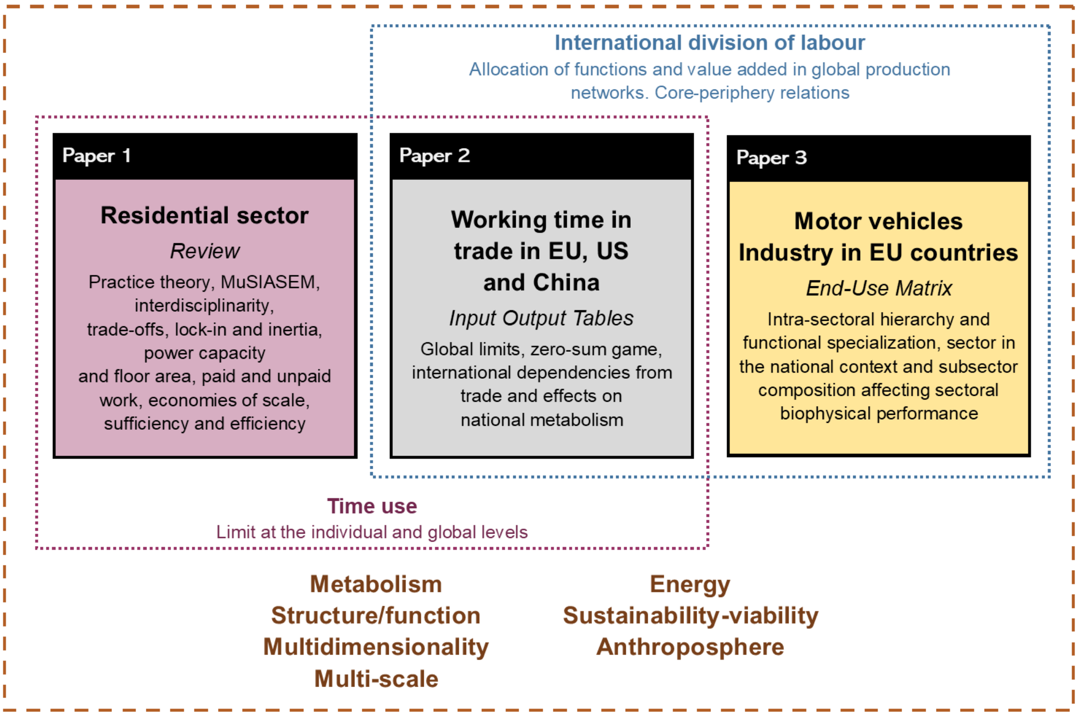


Figure 3 Case studies of the thesis and overarching topics and concepts

The analysis of viability includes issues such as the increased time pressure and hurriedness of daily life, household organization and their relationship to resource consumption, the internationalisation of production and the dependence on an increasing number and diversity of production processes around the world. More specifically, I explore the current state of economic sectors in European countries and the international division of labour, the broad array of proposals for possible futures of the residential sector from institutional to technical construction aspects. These analyses are mainly done for different European Union countries. These three case studies come from published or submitted papers. The relation between chapters and some main overarching concepts is shown in Figure 3.

The specific research questions and concepts addressed and explored in each chapter are:

Chapter 4:

Published paper: Pérez-Sánchez, L.À., Velasco-Fernández, R., Giampietro, M., 2022. *Factors and actions for the sustainability of the residential sector. The nexus of energy, materials, space, and time use.* Renew. Sustain. Energy Rev. 161, 112388. https://doi.org/10.1016/j.rser.2022.112388

- What are the key elements and factors for the sustainability of the residential sector in a metabolic and holistic perspective?
- How may strategies for the sustainability of the residential sector affect different dimensions involved?

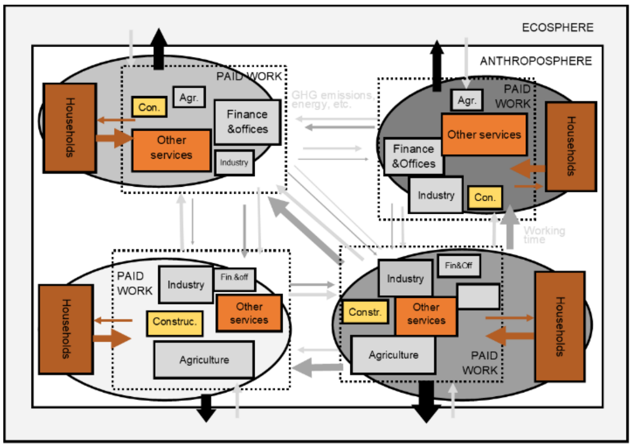


Figure 4 Highlighted sectors and relationships in socio-ecological systems considered within chapter 4, which analyses household metabolism

Chapter 5:

Published paper: Pérez-Sánchez, L., Velasco-Fernández, R., Giampietro, M., 2021. *The international division of labour and embodied working time in trade for the US, the EU and China*. Ecol. Econ. 180. https://doi.org/10.1016/j.ecolecon.2020.106909

I explore the general question:

- How does the embodied working time in trade affect national metabolic patterns and internal allocation of time?

Through this specific case study:

  - How much working time was embodied in trade flows between China, the US and the EU in 2011?
  - From which sectors and regions does this working time come?

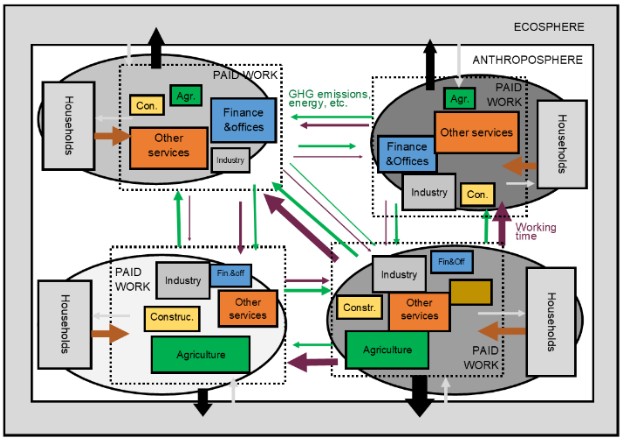


Figure 5 Highlighted sectors and relationships in socio-ecological systems considered within chapter 5, which analyses the effects in national paid work metabolism of embodied working time in trade

Chapter 6:

Submitted paper: Pérez-Sánchez, L.À., Velasco-Fernández, R., Giampietro, M., (submitted). *Energy metabolism of the automotive industry in European Union countries – implications of functional specialisation in biophysical performance*

I explore the general question:

- How do the different composition and function of a sector in a country affect its metabolic pattern?

Through this specific case study:

- What do the metabolic patterns of automotive industries in the EU in 2018 reflect in terms of function and hierarchy?
    - What is the size of automotive industries in EU countries?
    - How do their metabolic patterns compare to their national upper levels (paid work and manufacturing)? How do they compare between each other?
    - How different are the metabolic patterns of the lower level explaining more specific functions in the automotive industry?

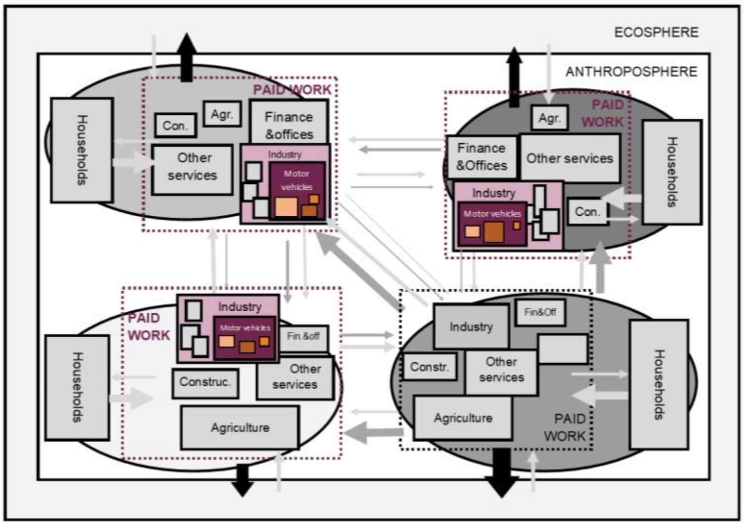


Figure 6 Highlighted sectors and relationships in socio-ecological systems considered within chapter 6, where I go a level lower to compare the Motor Vehicles Industry metabolism in 8 EU countries

The different chapters revolve around different sectors and methodologies. I do not only aim to unravel the internal dynamics of sectors but also the links, parallelisms, and differences between them. A reductionist perspective would determine that through the addition of the exploration of the individual sectors as isolated entities I could understand the whole system. Instead, I put in context holistically each of the sectors, to understand the relations between each other and any emergent properties and behaviors. Despite the variety of sectors and topics, the chapters do share more general concepts essential to tackle sustainability which are in many cases overlooked. I discuss these concepts and linkages in the conclusions.

In the following chapters, I provide an overview of theoretical concepts where the rest of chapters are based on. They are diverse, coming from different disciplines, and part of the work of this dissertation was its integration. These include the scientific context, the paradigm of ecological economics, the concept of metabolism and how it illustrates the functioning of socio-ecological systems, practice theory, and the quantitative approach based on the flow-fund scheme and MuSIASEM.

INTRODUCTION

1. The scientific context

The positivist Cartesian and Newtonian view of science has brought us both progress with new technologies and environmental impacts at local and global scales. Therefore, a transformation of the way science is made is necessary to address adequately the problems it has generated. The scientific context explains in part how holistic and interdisciplinary approaches are lacking, which are fundamental for sustainability analysis. This context includes the predominant positivist methodological approach, and the institution of academia. Some inherent characteristics of sustainability including incommensurability and the existence of social and therefore political aspects make fundamental an alternative approach to socio-ecological analysis and decision-making.

1.1. From reductionism to holism

The Cartesian view of science tends to divide problems into bits. Its objective is to find relations of causality based on experimentation and statistically significant data. Fragmentation and specialisation make us lose the holistic bird’s eye perspective necessary for system analysis. Silo science produces tunnel vision and single-problem framing (Kovacic, 2018), and specialisation and very specific jargon hamper the discussion between disciplines or even within the same field. For example, Kębłowski and Bassens (2017) identify three main groups in Brussels and their scholarly approaches to urban transport and mobility (neoclassical, sustainable and critical). The authors detail how the three groups identify key variables, problems, causes, and propose solutions differently. Each approach leaves out many potentially crucial issues, and this might lead to unexpected side-effects.

Likewise, sustainability is nowadays mainly narrowed down to climate change (i.e., carbon tunnel vision - Figure 7) or an energy transition to renewables. Models including only GHG emissions or energy production fail to consider in many cases the viability of the society and the trade-offs with other vital variables. For example, models with energy scenarios largely based on bioenergy but without including the variable land use may not adequately deal with the land use competition with biomass production for food, feed, materials, etc. Even though generating models with all possible variables is not feasible, at least we must understand the dimensions at play to be able to include the most relevant ones, to acknowledge the limitations of our work, or to anticipate side-effects.

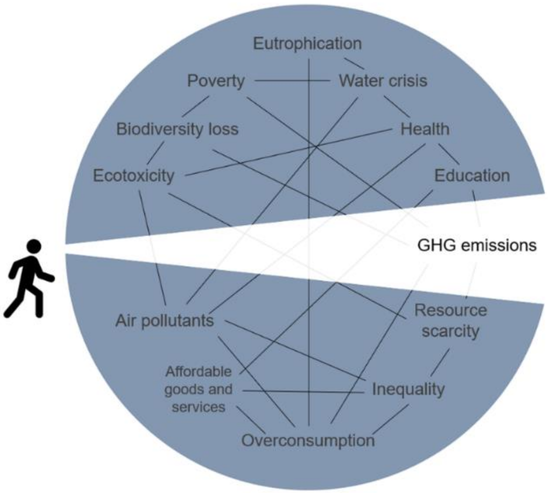


Figure 7 The carbon tunnel vision hides the many issues and dimensions of sustainability and their connections. This concept and graphic representation were coined by Jan Konietzko.

1.2. An unsustainable academic system

This fragmentation of fields is one of the factors that have contributed to the decrease in scientific breakthroughs in the last decades (Park et al., 2023). Now that we most need transformative ideas, it is when we have fewer breakthroughs. More knowledge, time and researchers are needed to produce new knowledge (Taylor and Tainter, 2016). As a result, innovation suffers from diminishing returns (Strumsky et al., 2010; Taylor and Tainter, 2016). This is especially important considering that, while even mainstream economists accept resource limits, they argue that these can be overtaken by unlimited human ingenuity.

Moreover, the ‘publish or perish’ academic culture also hinders the quality of research and the conditions in which research is done. These include little stability to sustain long-term projects, a lack of flexibility to change directions within projects to assess new questions that arise during research, and large amounts of bureaucracy, including grant writing and justification. The short-term of projects and contracts and productivity imperative in terms of number of papers generates only incremental advancement (if any). The system tolerates and even promotes the publication of many low-value papers as ‘minimum publishable units’ (Geman and Geman, 2016; Kirchherr, 2022). As a consequence, the number of published papers has increased exponentially. This generates an overflow of literature even in a single field, allowing the proliferation of duplicates. Let alone truly interdisciplinary work that aims to integrate different areas of knowledge, requiring more wide-ranging knowledge.

Moreover, interdisciplinarity requires collaboration between scholars, with enough time for building common ground and to go through broader literature. Only after this initial effort, truly disruptive transdisciplinary science can occur. However, this is a new paradigm in science with few prior experiences. In many cases, transdisciplinarity is figured out by trial and error with a high risk of failure (Kovacic and Marcos-valls, 2023). The ‘publish or perish’ context leaves little space to genuine experimentation.

Academic work for sustainability is made in a context of an unsustainable academic system, which produces an overwhelming number of papers and hinders holistic perspectives that integrate different dimensions and approaches. Transdisciplinarity is difficult and almost uncharted territory, and the context in which it is supposed to happen only makes it more challenging.

1.3. The quantification imbroglio

The Cartesian view of science assumes and is based on mathematical preciseness. Georgescu-Roegen described this arithmetic fetishism and abuse as "wholesale arithmetization" (Farrell and Mayumi, 2009; Georgescu-Roegen, 1971). Generally, scientific truths from "hard sciences" are constrained to a set of narrow conditions (temperature, pressure, etc.). The precision given in this kind of research is not useful in real life to manage social problems with a high level of uncertainty, and multidimensionality. In many cases, understanding the relations and rough numbers about relevant magnitudes is better than a precise mathematisation of irrelevant variables. This is the idea that Hobson coined as an "organic test of welfare" (Daly, 1968).

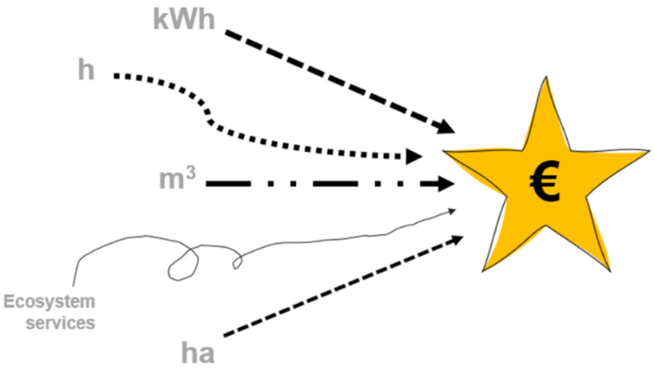


Figure 8 Quantitative analyses of sustainability, in many cases, collapse the multidimensional information into a single metric, typically monetary, which involves strong assumptions to convert a diversity of other units or incommensurable facts

This mathematization is strongly linked as well to collapsing all information into a single unit. A common single metric is required to perform optimization calculations, cost-benefit analyses, and to compare elements or options. This way, scholars estimate the 'social costs of carbon', and rank countries by sustainability or universities by their quality. Multidimensionality is usually collapsed to monetary values, whereas a growing number of composite indicators of wellbeing attempt to measure development in alternative ways to GDP. Other examples are exergy accounting or the ecological footprint. The great level of aggregation of this type of indicators does not provide enough information to describe the characteristics of a system and thus to guide policy (Giampietro and Saltelli, 2014; Munda, 2005). Moreover, value-laden and strong assumptions are the basis of conversion factors to monetary values for contingent valuation method, and normalisation, weighting and aggregation for composite indicators (Fix, 2019; Kovacic and Giampietro, 2015; Mayumi and Renner, 2022; Saltelli, 2007). These different valuation and prioritization methods result in different orders in rankings by composite indicators of wellbeing and sustainability, for example as shown in Becker et al. (2017).

The aggregation problem also happens at the level of products, even when we consider "the same" product. For example, there is a large number of different energy carriers (e.g., electricity, fuels) and primary energy sources (e.g., oil, coal, solar radiation) and their heterogeneity should be respected in quantitative analysis (Giampietro and Sorman, 2012). This product mix problem is exacerbated considering the enormous variety of industrial goods and parts that are currently produced. In chapter 6, I explore this aggregation problem with the production of vehicles and parts in the motor vehicles industry in different European countries. The same sector in different countries devotes itself to completely different products and processes, affecting its metabolic patterns.

Moreover, many relevant variables or factors are very cumbersome to quantify or are directly incommensurable (Funtowicz and Ravetz, 1994; Martinez-Alier et al., 1998; Munda, 2004; Vatn and Bromley, 1993). Despite this, many researchers assign them a monetary value, for example, with ecosystem services (Gómez-Baggethun and Ruiz-Pérez, 2011), what Georgercu-Roegen (1954) describes as an “ordinalist fallacy”. Even when goods have a monetary exchange value established by markets, this does not represent their use value. For example, a mere monetary accounting of food systems does not show whether the population is well nourished.

The End-Use Matrix within the MuSIASEM framework used in this dissertation is a multidimensional quantitative approach, acknowledging that many issues must be analysed qualitatively. I explain this in more detail later (section *3.1 MuSIASEM*).

1.4. Models and the exploration of possible futures

> *“But self-organizing, nonlinear feedback systems are inherently unpredictable. They are not controllable. They are understandable only in the most general way. The goal of foreseeing the future exactly and preparing for it perfectly is unrealizable. The idea of making a complex system do just what you want it to do can be achieved only temporarily, at best. We can never fully understand our world, not in the way our reductionistic science has led us to expect. Our science itself, from quantum theory to the mathematics of chaos, leads us into irreducible uncertainty. For any objective other than the most trivial, we can’t optimize; we don’t even know what to optimize. We can’t keep track of everything. We can’t find a proper, sustainable relationship to nature, each other, or the institutions we create if we try to do it from the role of omniscient conqueror.*
>
> *For those who stake their identity on the role of omniscient conqueror, the uncertainty exposed by systems thinking is hard to take. If you can’t understand, predict, and control, what is there to do?“* Donella Meadows (2016, p. 167)

If finding precise numbers (and numbers altogether) for a current or historical time is challenging or impossible, we should be aware of the implications of using numbers for future states and trends of society. The limited precision of weather models shows how even within purely natural sciences there are problems for forecasting (Smith, 2002; Thompson and Smith, 2019). When we include social aspects, the uncertainty and modelling challenges increase.

Mainly since the oil crisis in the 70s, there have been numerous exercises to explore possible energy futures that we can analyse whether they have been successful. Historical retrospectives of energy models have shown that long-term (and even short-term) “forecasting” has had limited success from a numerical standpoint, and even more when these are extrapolations of historical trends of the relation of GDP use to energy (Craig et al., 2002; Smil, 2003, 2000; Weinberg, 1979; Winebrake and Sakva, 2006).

Also, we might remember the low prediction power shown by mainstream economics not seeing the 2008 financial crisis coming. However, this might be caused by the weak framework of analysis instead of the fact that they use models (Kovacic, 2013). Hence, we should not talk about forecasts or predictions here but of exploration of possible futures or “what if” scenarios (Börjeson et al., 2006).

Models are tools that cannot reflect the reality in detail. They are abstracted, stylized and reduced versions of reality. In his short parable “*Del rigor en la ciencia*” Jose Luis Borges illustrated how a group of cartographers created a useless 1:1 map of a whole empire. This short story illustrates the statement ‘the map is not the territory’ by Alfred Korzybski. A single representation cannot explain all issues, elements and relations. When we address complex issues in the relational or Rosennian sense, we have a myriad of non-equivalent representations addressing different perspectives, levels and dimensions (Rosen, 1958). This is different from an “anything goes” perspective, though.

As the emblematic quote of George Box states: “All models are wrong, but some are useful”. Models are vertebrated by many assumptions, which make the results brittle and limited. Building models helps in finding other methods’ weaknesses and the pessimism or optimism towards future technologies, in understanding the need for different perspectives to model- and scenario-building, in generating estimations of orders of magnitude and reflecting on the relations between elements, etc. Some of these conclusions are shared by expert modellers (Meadows, 1982; Ravetz, 2003; Saltelli et al., 2020; Saltelli and Giampietro, 2017; Thompson and Smith, 2019; Weinberg, 1979). In some cases, models are tautological, and hypotheses define largely their results. This makes diverse participation fundamental.

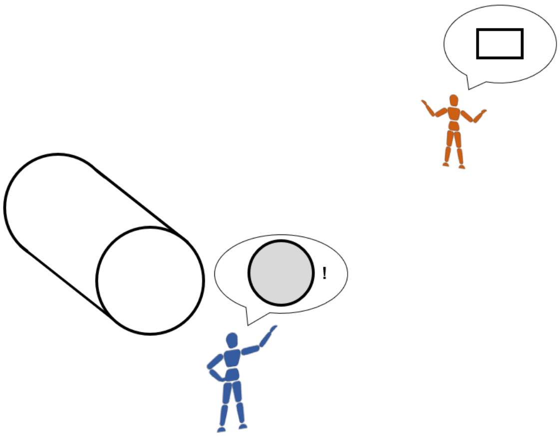


Figure 9 Different perspectives can come up with different valid representations.

One important part of sustainability science is envisioning possible futures, and another is the exploration of trajectories and drivers of transformation that allow us to get to those future states. Transformation is a concept close to that of transition. While transition generally refers a technological substitution of elements, transformation implies a more profound and radical change. Estimating the functions and relations in a model becomes impossible since there is a shift in the core identity and rules of the system. When we look at completely different future, with different infrastructure and culture, the current and historical dynamics are not followed and thus not useful anymore. One of the key questions in sustainability analysis is to identify the drivers and tipping points of transformation. Actors and scholars have suggested a wide range of possible transformation mechanisms, including incremental actions, organisational changes, individual or collective actions. There are different explanations for the transformations of the past for which we have information, let alone those for the future. For example, the causes to the use of fossil fuels during the XIXth century is explained differently by Debeir et al. (1991) and Malm (2013). Whereas Debeir et al. (1991) flag the scarcity of biomass and other renewable flows as the main cause for the tapping of fossil fuel resources, Malm (2013) points out the control over workers in comparison to the intermittence of hydro.

Many theories aim to explain transformation. In the next paragraphs, I present some of them to show the diversity of views on this fundamental idea. These go from political views to more technological assessments. For example, Dahle (Dahle, 2007) distinguishes four profiles based on political views: reformists, impatient revolutionaries, grassroots fighters, and multifaceted radicals. These archetypes differ in three items: whether solutions exist within the existing order, if these are top-down or bottom-up, and whether or not the transition is possible now.

There is a fundamental debate on the power of the individual and small-scale changes to generate macro-changes. Those with the assumption of rational choice of individuals generally propose carbon taxes to correct “imperfect” price signals allowing consumers small scale decision-making. On the other hand, authors like Fred Hirsch (1977) explain that piecemeal or marginal decisions, which are the base of agent-based models, do not allow us to choose between alternative states.

Donella Meadows (1999, 1982) also considers these small-scale changes as one of the least-powerful ones to transform systems. She listed 12 points to intervene in a system and ordered them in effectiveness, from constants, parameters and numbers (such as subsidies and taxes) to the power to transcend paradigms (i.e., to change the paradigm where goals, structure, rules, delays, parameters arise from) (Meadows, 1999, 1982).

One of the most famous theories of transformation is Frank W. Geels’ multi-level perspective (Geels, 2011, 2002), where radical innovations emerge in niches, then compete, and at some point, they might become more stable elements of the socio-technical regime.

1.5. Sustainability for policy

Sustainability science works at the science-policy interface. Science for governance is key in social and technological transformations in order to inform those making policy. There is a fake expectation of command and control and causality in decision-making. This is, in part, framed within the Cartesian vision of science. Politicians claim the use of “scientific evidence”. This way, their political responsibility is backed by an external trusted institution. In many cases, they cherry-pick evidence matching their political vision and agenda from the broad variety of issues, dimensions and perspectives that can be analyzed about a single topic. Governments have power in the funding process of science and, therefore, have a certain decision power in what science is worth funding (Saltelli and Giampietro, 2017; Strassheim and Kettunen, 2014). In this sense, we should talk about ‘policy-based evidence’ instead of an allegedly objective evidence-based policy.

Sustainability problems should be framed in the paradigm of ‘Post-normal science’ (Funtowicz and Ravetz, 1993), where ‘‘facts are uncertain, values in dispute, stakes high and decisions urgent’’. (Funtowicz and Ravetz, 1993, p. 744). Governments declare to base their work on evidence, but at the same time the social and technological contexts are complex and decisions are taken in a context of urgency and unavoidable uncertainty that cannot be solved by increasing research (Benessia et al., 2016).

Scientific knowledge and technical and social innovations develop at the same time as action must be taken. For example, when climate-change-induced disasters such as hurricanes or droughts happen, scientists generally point out that we cannot categorically state that these phenomena are induced directly by climate change and human action, only that these kinds of events are more frequent due to climate change. It is only after years of research that this can be proven. Also, many technologies that are included in models as a solution to decarbonisation, like carbon capture and storage or green hydrogen, have had, so far, limited implementation. Therefore, their potential and characteristics can only be estimated until they become more established technologies. This ‘post-normal science’ paradigm has also become clear with the COVID-19 pandemic. The measures to limit infections had to be considered in the economic context and the capacity of the medical system, which had to cover this illness, the rest of patients and mental health.

Moreover, in the reflexivity paradigm where sustainability problems are situated, we must also consider values and social dynamics (power, participation, etc.), non-quantifiable parameters (Kovacic and Giampietro, 2015; Martinez-Alier et al., 1998). The groups of interest have different weights in the decision process and are affected differently in the dimensions at play. Some actors can directly receive the impacts while others get the profits. Observers, including of course the same modellers and analysers, have their own perspectives and representations of reality. The same definition of the problems can be different depending on the perspective of the observer, let alone the proposal of solutions (Di Felice et al., 2021b). We cannot optimise because we do not have a common meaning of what is best. We are looking for compromise solutions: “good enough” solutions and option spaces to generate a democratic debate. However, finding this option space is already a challenge.

One of the first steps to approach sustainability issues it is to find out the positions and perspectives of the different actors. In relation to this point, chapter 5 illustrates the effects of the international division of labour in working time embodied in trade and how different regions receive extra working time embodied in imports while others provide it.

We can also define sustainability as a wicked problem (Rittel and Webber, 1973). This is a problem where many perspectives and dimensions come together. These are not reducible to a common unit. Different goals are in tension, and we need to find compromise solutions. If we do not see the whole picture, we could otherwise release pressure on one dimension while increasing it in others, potentially overshooting them. For example, biofuels are produced with renewable resources and were told to be a solution against fossil fuel depletion and climate change impacts. However, their production occupies large amounts of land uses, limiting their production on a yearly basis and competing with other agricultural end uses such as food. This way, the pressure over fossil fuel reserves could decrease to a limited extent by rising the pressure over land uses. Therefore, we find connections to other systems and side-effects through dimensions that were not as important in the fossil fuel production compared to biofuels. We have seen that the pressure generated by the biofuel blend mandates in the US and the EU has raised price in food products that have affected more strongly the poor (Malins, 2017).

2. Theoretical framework

After explaining some key issues regarding the general scientific context that affect sustainability science, in this chapter, I explain the ecological economics and social practice theoretical framework where the case studies are grounded.

2.1. The limited view of conventional economics

Economics is the social science that analyses the production, distribution and consumption of goods and services. In its conventional approach, monetary and financial aspects take centre stage. This is clearly shown in the following excerpt from the System of National Accounts (SNA) guidelines, considering that SNA is *"the internationally agreed standard set of recommendations on how to compile measures of economic activity in accordance with strict accounting conventions based on economic principles"* (European Commission et al., 2009, p. 1)*:*

> *"**4. Accounting rules***
>
> *3.14 All entries in the accounts have to be measured in terms of money, and therefore the elements from which the entries are built up must be measured in terms of money. In some cases, the amounts entered are the actual payments that form part of flows that involve money; in other cases the amounts entered are estimated by reference to actual monetary values. Money is thus the unit of account in which all stocks and flows are recorded."* (European Commission et al., 2009, p. 40)

This states that the "strict accounting conventions" define that the unit of economic activity is money. Standard economics stylises the economy as a perpetual motion machine of circular flow of GNP production without external inputs from nature (Figure 10). Of course, all models are simplified versions of reality, but we can ask if that is a too large simplification (Ehrlich, 1989). If any other dimensions are ever considered, they are translated to monetary values, including all kinds of capital, wants, needs and externalities. This flattening of dimensions is made through value-laden conversion factors, as explained previously (section *1.3 The quantification imbroglio*). Moreover, after that first simplification, conventional economists induce causality through complicated regressions and equations such as those in general equilibrium models. The apparent sophistication of mathematical modelling hides a simplistic worldview, what Reinert (2009) calls "terrible simplification".

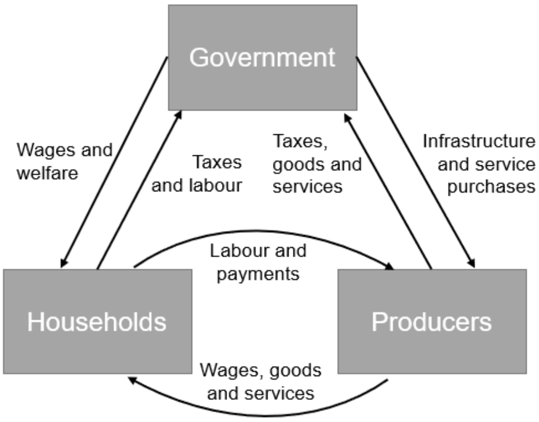


Figure 10 Mainstream economics represents the economy as a circular flow of income. The environment does not appear.

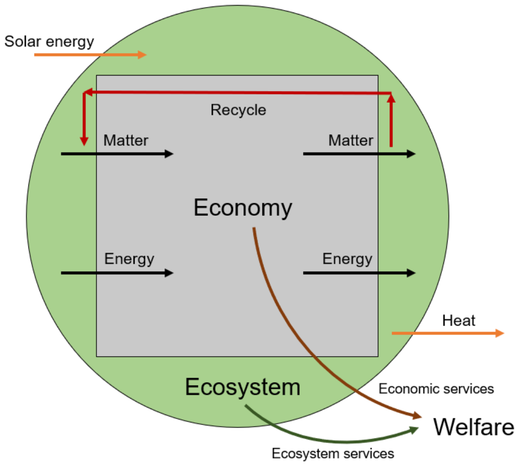


Figure 11 For Herman Daly, the economy is a subsystem of the environment, and it has an entropic nature (Daly, 2005)

Nature and production processes are not well represented in conventional economics. This limited ontology might explain how the financial economy is growing in a way that no longer maps on biophysical flows. Kovacic et al. (2018) found that from 1995 to 2013 financial assets per unit of income and per hour of work increased in all countries and sectors. Some scholars have claimed a return of debt related to reserves, balancing investing and saving (Daly, 2016, 1980). However, money and debt are, in fact, biophysical debt: the expectation of future economic activity related to material transformation, committing future material flows and impacts (Melgar-Melgar and Hall, 2020; Renner et al., 2021). Moreover, since debt grows with compound interest, we should expect resource use to grow as well with compound interest to repay it when currently it is already overshooting global limits. This expected increase adds to one of the main problems of the current socio-ecological regime: its already currently too large scale, whereas conventional economics usually focuses on problems of allocation and distribution (Daly, 1992). Human appropriation of resources, infrastructure, population and other impacts have increased exponentially during the last decades (Smil, 2019; Steffen et al., 2015). In conclusion, conventional economics only considers part of the picture, dismissing or not properly representing fundamental processes and sustainability issues.

2.2. An alternative paradigm: Ecological economics

The economy should not be considered merely as the exchange and flows of money but also as the production processes, material flows, etc. Money drives the exchange of labour, services and goods, while energy fuels machines and drives extraction, transport, manufacturing, etc. Also, agriculture and forestry provide vital inputs for food and other end uses. I could keep the list going. The economic process is rooted and embedded in natural processes. This connection of society and nature is displayed in the concept of Socio-Ecological Systems (SES): "*Social-ecological systems are complex adaptive systems in which people and nature are inextricably linked, in which both the social and ecological components exert strong influence over outcomes. The social dimension includes actors, institutions, cultures and economies, including livelihoods. The* *ecological dimension includes wild species and the ecosystem they inhabit*." (IPBES, n.d.).

Parallelisms and analogies to natural sciences have fed and changed the economic paradigm. Nicholas Georgescu-Roegen (2017, 1977) presented the term of bioeconomics. This term acknowledges the link between nature and the economic process that already existed in his previous work (Carpintero, 2005). Similarly, Herman Daly (1968) considered the economy as a life science. Howard T. Odum (1973, 1971) applied systems ecology to the flow of energy in the economy, for example, when he compares energy transformations to food chains. The list of concepts taken from biological sciences goes on with terms such as metabolism, reproduction, synergy, anabolism and catabolism.

The socio-economic system is inserted within the environment and depends on the quality and quantity of its inputs to survive (Figure 11). Living systems (Schrödinger, 1944) are dissipative structures (Prigogine and Stengers, 1984), which feed on negative entropy inputs and discard high-entropy outputs to its environment. The external support system of the dissipative system must admit those outputs that it receives, and be able to provide the inputs that the system requires. The economic process consumes negative-entropy inputs such as primary energy sources and raw materials, while it dumps high-entropy wastes, contamination and heat. With these external resources, socio-ecological systems must reproduce its components and evolve in time. The openness of these systems makes it difficult to define a boundary distinguishing them from the environment (Mayumi and Giampietro, 2004).

Therefore, as Georgescu-Roegen (Georgescu-Roegen, 1971) presented, the economy is regulated by the laws of thermodynamics and irrevocably tends to maximum entropy, both for energy and matter. Energy is eventually dissipated into heat while materials are degraded: abraded, rusted, ravaged and rot. There is an unnegotiable entropic and irreversible nature of the economy. We cannot expect it to be fully circular (Cullen, 2017; Giampietro, 2019).

When we say that society has a metabolism, this goes beyond a mere metaphor or parallelism to organisms and ecosystems. In part because we depend on the inputs that come from nature, whose extraction and transformation follow natural or biological rules. Also because, as I've explained previously, society feeds on negative entropy inputs from the environment to feed the internal components (e.g., countries and sectors) similarly to what happens in bodies. Lotka (1956) differentiates between the biological processes within human bodies (endosomatic metabolism) and the processes outside skin related to commodities and other flows in the anthroposphere, i.e., under human control (exosomatic metabolism) (Daly, 1968). The concept of metabolism will be used in the following sections to explain some key characteristics of socio-ecological systems.

2.3. The evolution of Socio-Ecological Systems

Socio-ecological systems, like other living systems, are in a state of continuous becoming and evolution. Changes will be observable at a certain point depending on the scale of the system and the relative size, tools and skills of the observer. While most people do not perceive in our lifetimes with the naked eye many long-term geological changes such as mountain movements, some scientists and engineers can measure them through specific equipment. With a timescale of months, years and decades, this continuous becoming also happens with the human life stages that we can perceive. People are born as babies, become adults through infancy and end their lives as elderly, if they get to live long enough (Figure 12).

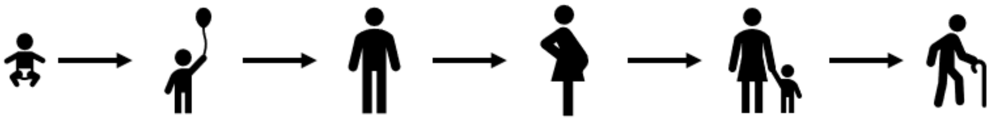


Figure 12 Individual humans are becoming systems with a changing metabolism whose evolution in life stages in general terms is predictable

This evolution changes the identity and the requirements for maintaining the structures in socio-ecological systems. For example, a baby drinks milk, and a teenager requires food both for growth and for carrying out activities. Similarly, different historical eras have attached different energy requirements, from biomass-based economies to the current fossil-fuel-based regime (Cook, 1971; Debeir et al., 1991; Smil, 2008). However, while we can describe in general terms the expected evolution of a newborn as an organism that grows into an adult (for example, height increase, hormonal changes, etc.), we cannot predict the evolution of socio-ecological systems as the constituent components and the rules governing the relations between sectors, nature and people change (Figure 13). In this sense, the low predictability of the evolution of socio-ecological systems is more similar to that of the evolution of species than of specific current individuals. This continuous evolution together with the nested entanglement and multi-scale structure makes the identification of drivers of change of the system and the assessment of policy that can lead to deep transformations a challenge.

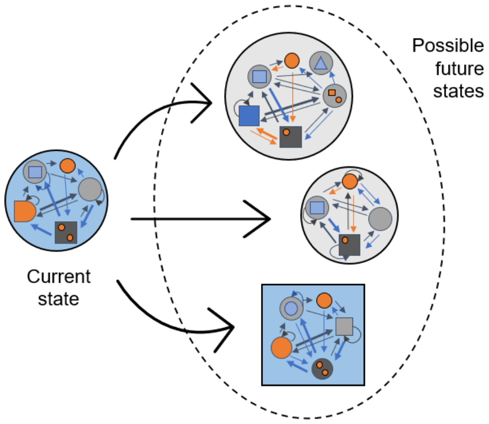


Figure 13 Socio-ecological systems are complex becoming systems whose configuration and organisation evolves in time and are not predictable, as their identity, elements and internal and external relations change

One example of this change in identity and structures in socio-ecological systems is the Jevons' paradox, where a relative improvement of technology allows the system to provide new functions and ultimately increase overall energy carrier consumption (Giampietro and Mayumi, 2018; Labanca and Bertoldi, 2018; Polimeni et al., 2008). For example, back in history, cars were smaller and less comfortable. Smaller ICV cars in the past have similar fuel economies to current larger ICV cars (Danilecki et al., 2017; Sprei et al., 2008; Wolfram et al., 2020). These relative technical improvements has not resulted in significant fuel efficiency improvements for the average car since the average size of cars has increased (ICCT Europe, 2020). Moreover, further technical improvements have been introduced, such as air conditioning and a myriad of entertainment and driving help electronics. On average, cars in most developed countries have evolved from a rather uncomfortable transport mean to a convenient and vehicle full of entertainment increasing their size with the generalization of SUVs and average value as status sign. These changes make the use of cars more convenient, and therefore they are used for longer and more frequent trips. Moreover, car production, ownership and use influence as well other concomitant sectors (urban form, time use patterns, etc.), which crystallize the changes and can generate a lock-in of car use (see section *The system of automobility*).

2.4. Structures, functions, and practices

The concept of metabolism entails an organization of internal parts. Just as an organism and its organs, or an ecosystem and its species, socio-ecological systems are made of entangled components that perform functions allowing the functioning of the whole.

Complexity arises because structures and functions have a many-to-many relationship (Giampietro et al., 2006; Giampietro and Mayumi, 2018; Louie and Poli, 2020). Many structures can perform a given function, and the same structure can perform many functions at the same time. For example, cars and buses can move people around in cities (same function with different structure), while cars can be as well an object of social distinction, a private vehicle, a taxi or a vehicle for providing at-home care, and a product of the automotive industry for exports and generation of employment and value added in a country (one structure with many different functions).

Sustainability does not require only a mere substitution of devices or structures, for example, the electrification of car fleets. It also requires understanding well the functions that the devices perform and the needs and wants of society, in the line of sufficiency approaches (Lorek and Spangenberg, 2014; Spengler, 2016). This way, we could think of deeper changes such as new organization and rules of the system, for example, all kinds of sharing which generate economies of scale. Within the function “mobility”, we could change the private vehicle model to carsharing and public transport services. However, the thorough analysis of the function could leave us space for decreasing altogether travelled distances through cultural and organizational changes, for example, regulating maximum distances from homes to workplaces. Within the leisure and education activity of “reading”, books could be manufactured in paperback instead of hard cover, and this would entail a decrease in paper requirements for a given book. This would be an example of the narrowest definition of efficiency. However, we could think in a more systemic way. The same item “book” can be borrowed in libraries instead of purchased and owned, decreasing the need for paper and storage space by way more. However, a change to the library model would entail providing alternative livelihoods to authors, editors, printers, etc. and investment in spaces and salaries for library workers.

Changing the social organization will most surely also require different devices, provisioning systems, infrastructure and income or livelihood sources. In this dissertation, this kind of analysis is mainly done in chapter 4 on the residential sector. There, I analyse household units, their functions and organization, mainly based on the nuclear family and an increasing individualization. The institutions that conform households could be rethinked. Also, activities carried out at home could be complemented by the community and activities in paid work, improving economies of scale and shareability.

2.4.1. Practice theory

We explain the relationship between structures, their use and evolution through practice theory (Reckwitz, 2002; Rouse, 2007; Shove et al., 2012). This is a middle ground way of thinking between structuralism and ontological individualism where agency and structure interact (Shove, 2004). Structuralists consider the system and infrastructure as the only determinant of people's behavior. Structures refer to the physical and institutional frameworks such as hardware components like wires, pipes, and power plants, and intangible systems such as laws, regulations, and policies that govern social interactions and organizations. For other scholars, individuals are the basic unit of analysis. Their behavior is assumed as rational and their choice power in consumption and investment is considered a key driver of socio-economic change. In practice theory, the individual is not an autonomous member of society. People act according to what institutions and existent infrastructure allow them to do according to their expectations. This way, the focus of study is not on "individual behavior", but on the social patterns shared by groups of people.

Practice theory defines three key elements: materials, meanings, and competences (i.e., equipment, images, and skills) (Røpke, 2009; Shove et al., 2012) (Figure 14). To this triad, we could add other factors such as income. These three elements are interrelated, coevolve and are subject to continual reproduction. Competence (skill, know-how, technique) is built through time in education and culture. The material elements (devices and infrastructure) make possible and limit the allocation of time uses in different ways. For example, the availability of kitchen appliances and type of outputs of the food industry will partly determine how much time we spend in cooking and eating. However, other aspects such as food culture also influence it, which is different in Spain and the Netherlands, for example. It is not the same to eat one or two courses for lunch than a simple cheese sandwich. Meanings are the cultural conventions and the expectations of people. These depend on the existent and expected material base, among other factors. Devices materialize culture and at the same time affect the social organization option space. For example, an expansion of a highway at the expense of public transport investment could come from a car-centered society and reinforce this car dependency and car culture.

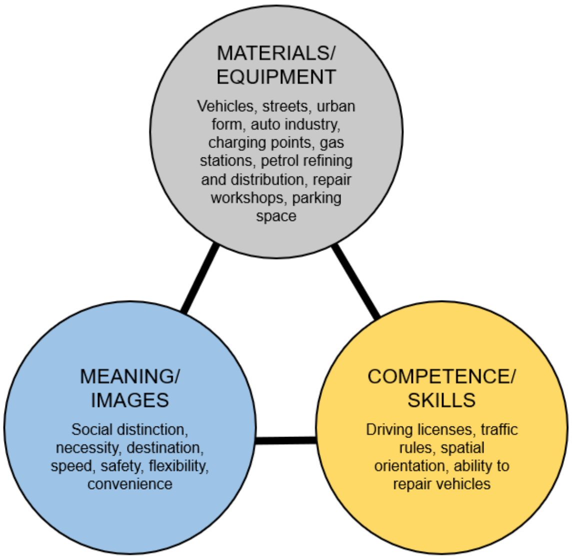


Figure 14 The three basic elements of practice theory, with examples of the use of cars

As any other socio-ecological entity, practices are not static. They diffuse, compete and disappear. Practices are related to each other in constellations or bundles. I have not introduced yet the concept of funds and flows (see section *3.2 Flow-fund scheme*), but part of this competition is for the funds, which determine clear limits to the system: power capacity (devices, machinery, etc.), land use and human time. In terms of daily life and families, the role of time is fundamental and at the core of decisions: daily life must be built within a limited budget of 24 h/day, the existent infrastructure, the needs and wants of individuals and those around them (e.g., dependent people) and the duties taken within the community such as paid work. This limit is experienced by every person in their everyday life and is a key element in understanding the societal evolution in the use of natural goods.

Therefore, there is not a single direction of causality or determination, but a co-evolution of the three elements of practice theory. We have a context-dependent evolution and self-reinforcing systems with chicken-egg relations. Escaping these trends and shifting the system towards a different evolution is a challenge. As I explained previously, there are many theories that aim to explain transformation. It is very difficult to estimate tipping points or to identify transformational changes *ex ante* and even to explain their causes *ex post*. There is not really a way to verify that a theory of transformation is true. However, practice theory and other concepts can give us hints about hurdles and options for change.

2.4.2. Lock-in: committing practices and impacts

Large long-term investment decisions on infrastructure influence piecemeal daily decisions taken by individuals. Infrastructure design limits the ways that people can use it, jeopardising the future use of resources. This concept was coined as lock-in, with three main types: (i) infrastructural and technological; (ii) institutional; and (iii) behavioral (Fisch-Romito et al., 2021; Seto et al., 2016; Unruh, 2000). We can find parallelisms of this classification to the practice theory. Lock-in has been mostly analyzed for the energy system and manufacturing, for example with the committed emissions from existing energy infrastructure (Tong et al., 2018) or the blast furnaces phase-out (Vogl et al., 2021). Lock-in can lead either to committed resource use of the future or to stranded assets, when resources are not available for their functioning or other causes makes them not usable anymore. We can imagine a newly built airport in a context of kerosene shortages, irrigation canals in an arid region when rainfall decreases or buildings on the sea front when sea level rises.

These technical structures generate lock-in and are the base for material path dependency. However, we can find other examples. Sometimes decisions taken in the design stage are quasi-irreversible and define the future investments and the knowledge and skills that is required by the people that are going to use them. There are examples of relatively trivial questions such as the QWERTY typewriter (David, 1985). The configuration of the keys in the keyboard was determined in its introduction as a technical object in society. Afterwards, there has been no possibility to change this even though this configuration might not be the most efficient. I assume that most people reading this dissertation commonly type in their daily life. If there were a change in the configuration of keys in new keyboards searching for a typewriting maximum speed, it would be uncomfortable at first. It would take time to adapt, and both configurations would coexist for some time as long as devices are in use, requiring flexibility by users who would find both type of devices.

However, the critical issues for sustainability are not the path dependency given by relatively insignificant technical configurations such as the QWERTY typewriter but of the evolution of infrastructure and the built environment. Another paradigmatic example of path dependency are rail gauges (Arthur, 1990). The initial decision of design defines the future additions to make them compatible to the existent system. National differences in rail gauges have hindered the internationalisation of train services.

Infrastructure has an enormous embodied investment and sunk costs. Decisions taken on the initial design stage determine largely its future use for long periods of time due to their durability. For example, a car-centered urban form will generate car dependency for decades, requiring an availability and supply of private vehicles (Pérez-Sánchez et al., n.d.). Cars are in use for decades, whereas buildings and other infrastructure can be in place for centuries. In developed countries, the existing infrastructure generates lock-in and committed emissions and practices. This generates a dilemma of what to do with a system that requires large amounts of fossil fuels to operate.

In developing countries, many of these investments are still to be made. This is a sign of a lack of services for current citizens. However, if developing countries follow the infrastructure levels of developed countries with current technology, the carbon budgets for 2^{o}C are likely to be compromised (Müller et al., 2013). Still, it could be possible for them to leapfrog with new ways of development and practices, benefitting from lessons learnt in developed countries experience and thinking outside the box with social and technical innovation (or even tradition).

There are some fundamental decisions that set the playing game for practices and commit future resource use. These strategical and design decisions are taken by companies, management teams and governments, which also depend on the existing factories and resources and what they expect citizens to purchase or demand. For example, the automobile industry provides ever larger cars, such as SUVs. These require investments in factories to adapt for the production of these bigger cars that must be repaid. The ever-increasing variety of SUVs models replacing compact cars leaves little space for decision of individuals and families which purchase cars. Individual's consumption works at the micro-level. In the end, the aggregation of micro-level final consumptions matches the macro-level decision taken by companies which decide to provide a given good manufactured in global production networks.

Two pillars of practice theory are related to culture and they can generate lock-in too. These are different types of system resistance or inertia to shift the whole paradigm or culture to another. On the one hand, this is reflected in the expectations and meanings of people: ideas of convenience, cleanliness, social distinction, safety, etc. An example would be decision of using private vehicles despite having access to public transport due to the sense of freedom and convenience. These impact infrastructure construction, for example, when citizens are not willing to vote for politicians that would invest in public transport. But of course, different actors have different power levels. Influential groups can affect citizens' opinion or directly decide on the investments, namely an institutional lock-in.

On the other hand, competence and skills, and regulations are essential to the functioning of socio-ecological systems and therefore can be a hurdle to regime change. New skills must be developed by people by learning and habituation. Teachers and professors must also learn to teach those new skills, which takes time and other resources. For example, regulations and common professional knowledge and practice can be hurdles to shift from concrete to timber structure in buildings (Pérez-Sánchez et al., 2022) (chapter 4). This is a different cultural challenge to people not liking timber buildings, not belonging to the traditional landscape or not being considered modern.

The system of automobility

The system of automobility could be considered as a systemic lock-in towards ownership and use of the private car (Sheller and Urry, 2000; Urry, 2004). This is an example of practice theory, lock-in and path dependency in the context of use of cars. The system of automobility generates a self-expansion of the system. First, society produces a new technology. This is slowly introduced until it becomes quite common and generates new normalities. For example, owning a car allows being wherever and whenever is needed. When someone buys a car, its lower marginal cost of mobility also locks-in the future use. When there is a significant car ownership, readiness to travel longer distances for commuting and flexibility might be normalized. This is a clear example of how expectations and devices from social practice are intertwined. The deployment of a device can also affect other technologies or material elements. In this case, the generalization of the car has enabled new types of built environment and vertebrated the territory, for example with suburban sprawl. This built environment will force car ownership to have a viable life. The decision taken when building dwellings locked-in and generated path dependency regarding the mobility that is coherent with it. This reinforces and maintains the system of automobility as long as the built environment is in place.

The system of automobility also generates or reinforces provisioning systems. This car dependency makes the automobile industry a basic pillar of the economy. On the one hand, it provides vehicles to the population, and on the other hand also generates value added. In chapter 6, I analyse the metabolic characteristics of the Motor vehicles industry in 8 European countries and its relative size within the national economy. This also happens with the broad network of gas stations and petrol energy system, from oil wells all around the world to refineries. With the potential electrification of fleets, not only the same vehicles must change, but also a parallel charging infrastructure must be built.

2.5. The economy as a network of entailments

Just as organs in a body are interconnected and function in a coordinated way, socio-ecological systems are composed by many elements that are intertwined at different geographical and temporal scales: from atoms, to cells, organs, individuals and families, sectors, countries, and the global economy. These elements are connected through flows of materials and information.

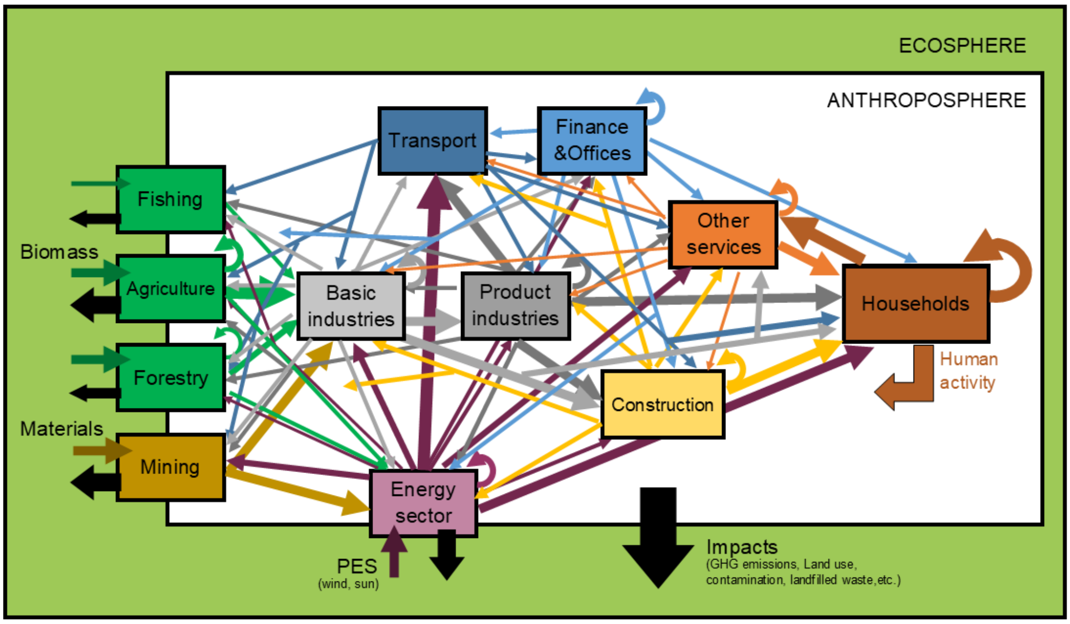


Figure 15 (Non-exhaustive) entanglements between sectors in the anthroposphere. Colours of the arrows are related to the outputs of each sector, for example, outputs from construction are represented by yellow arrows.

Within the global socio-economic system, sectors produce outflows and consume inflows as species do in ecosystems (Figure 15). They are both anabolic and catabolic depending on the flow of analysis. In cell biology, anabolism refers to the synthesis of new molecules inside the cell whereas catabolism are the metabolic processes involving the breakdown of existing molecules to supply inputs to anabolic processes. The outputs of a given sector are inputs for itself and others in a network of material entailments. The material entailments in the socio-ecological system are defined and constrained by the characteristics of the sectors and its components in terms of capacity, power, land, working time and other requirements (i.e., the funds, flows and flow-fund relations: see sections *3.2. Flow-fund scheme and 3.3. Production recipes, substitutability, and* *dilemmas*). This generates mutual information and causal impredicativity, what Giampietro and Bukkens (2015) call the Sudoku effect.

These couplings generate a dynamic equilibrium in a form of a network instead of linear series of transformations (Giampietro et al., 2012). These relations are continually changing, and thus the whole system's identity and metabolism changes with them. If there is a surplus of a certain coherent set of flows, the system might be able to build new structures and expand. This will demand further flows for their functioning in the future.

This complex network of inputs and outputs generates a mutual interdependence. We cannot simply eliminate the most impacting activities without considering how their outputs feed other sectors, and analyze if they can be substituted. Similarly, we cannot now declare that a single sector, company, or product is sustainable, since it requires inputs from other sectors and even the functioning of distant sectors maintains the monetary flow running. These dependencies entail that only if the whole system is sustainable, its parts will be sustainable. This makes concepts such as "sustainable cities" or "sustainable consumption" useless and obliges us to have a holistic systems perspective.

These entanglements are most commonly represented and calculated through Input-Output Tables. These were created by Wassily Leontief (1947, 1965, 1951). Despite the interest in representing the flow of goods and services between sectors and countries, the accounting is in monetary terms. At best, the numbers in an input-output table approximate the transactions of the economy in a given year. The construction of a multi-regional input-output table is a laborious operation that requires collection of data from several sources and types (supply-use tables, national input-output tables, national accounts, etc.) and already a series of hypothesis for consistency, harmonization, matching, confidential data, etc. (Dietzenbacher et al., 2013; Filchakova et al., 2007; Stadler et al., 2018; Tukker and Dietzenbacher, 2013). The centrality of monetary variables and lack of key biophysical information in IOT and do not represent well production processes. The use of a single variable helps the operationalisation, but it is still a simplification. These tables have been complemented with environmental and social extensions that explain the characteristics of each country-industry: all kinds of emissions, land use, working time, etc. However, these still lack a description of the functions, material inflows and outflows, services provided and capacity of each sector in each country and they assume industry homogeneity. This makes that changes in production and a transformation of the system involve large amounts of hypotheses.

2.5.1. Sectoral division of the economy

There is a primary division to the economy based on the generation of income or requirement for payments: inside (market and state) or outside paid work (communal or more generally, domestic). Households (together with some services) are the institutions that carry out care activities and reproduction of individuals. These sectors represent the anabolism of Human Activity. Their functions include short-term and daily needs such as eating and sleeping and long-term reproduction of population. These activities are required for households to provide employment to paid work, receiving salaries in return, among other monetary flows. Households get products and services from paid work. This primary division divides what conventional economics counts always in monetary terms ("the official economy") and what considers as a mere consumption agent (households).

In some cases, the same activity can be produced at both sides of the boundary: for example, food preparation at home or at a restaurant, production of breastmilk or powder milk, and elderly care at home or in a nursing home. There is a relationship of women's participation in the workforce to the level of tertiarization of the paid work economy, in part related to marketization of household production (and the creation of other types of public welfare state) (Freeman and Schettkat, 2005; Olivetti and Petrongolo, 2016). This way, activities on one side of the boundary are accounted for GDP and National Accounts while on the other side they are generally not accounted for (DeRock, 2021; European Commission et al., 2009). Feminist economists have pointed out the importance of generating a proper accounting of unpaid work (Carrasco Bengoa, 1988; Folbre, 2006; Wærness, 1978; Waring, 2003), with alternative national accounts such as Household Satellite Accounts (Holloway, 2002) or National Time Transfer Accounts (Rentería et al., 2016; Vargha et al., 2017). Here, the invisibility of this kind of economic activity to conventional economic accounting flags again the importance of time use accounts and the caveats of using monetary values as the central and only variable. These are essential activities for the functioning of socio-ecological systems.

We can find visions of the future and sustainability proposals that shift activities from one side of this main boundary to the other. On the one hand, some degrowth scholars envision a future more amateur economy based on reciprocity relations and communing care work (Dengler and Lang, 2022). Other researchers like Gershuny (1978) predict that the economy will be more self-service. In this case, products are not finished within paid work, but they require a final step within households, for example ready-made food or IKEA furniture. On the other hand, product-services are business models take out of homes activities and devices to be provided by companies instead. These services go from mobility-as-a-service, to the control of heating (i.e. providing a certain temperature level to a space instead of merely selling the climatization devices). The balance between viability of wages and payment of services at a competitive price in comparison to ownership is a key issue yet to solve in these product-services (Mont, 2004; Tukker, 2015, 2004).

This functional shift from households to communities or paid work is also related to a change in scale, which determines different structures and thus metabolic characteristics. Whereas paid work is made of large systems and international networks, domestic life is becoming increasingly individualized in developed countries. This entails a multiplication of household devices, for example, fridges and washing machines, since ownership is at the individual or household level. The functional and structural shifts between paid work, community and households are further analysed in chapter 4.

The shift of functions can also happen within sectors in paid work. For example, deindustrialization processes understood as the decrease in employment in industrial sectors, can be explained partially by the separation of engineering and ancillary tasks in specialized companies to which the tasks are outsourced. This functional fragmentation and reallocation come with the shift in energy use, GHG emissions and other impacts and profits. This makes more difficult the accounting and comparison of sectoral metabolism in time or between countries. The cause of changes in performance of a sector could be due to technological or functional changes. Within the same sector in sectoral classifications as broad as NACE and the detail given in national accounts, we can find differences due to the functional heterogeneity, as it happens in the automobile industry (chapter 6). In this case, part of manufacturing of parts and lower-range vehicles was shifted from core countries, for example Germany, to peripheral countries (e.g., Eastern European Countries) generating functional specialization and being reflected in their metabolic patterns.

2.5.2. Global production networks

The daily movement in the global North of taking a product from a supermarket shelf to the shopping cart is one of the last movements in enormous global value chains. Our consumption connects us with hundreds of workers around the world in agriculture, mining, manufacturing, etc. Food in supermarkets might represent rather simple value chains that can be in fact rather short in countries like Spain for some products, compared to other goods with complex and specific designs which involve a large number of parts and materials such as vehicles or electronic devices. These production networks work at the global level with many interdependencies that are in fact quite fragile in front of supply cuts, as we have seen with the microchip shortages in the last years. The complexity of devices has increased, and for example the microchip supply shortage would not have been as important decades ago.

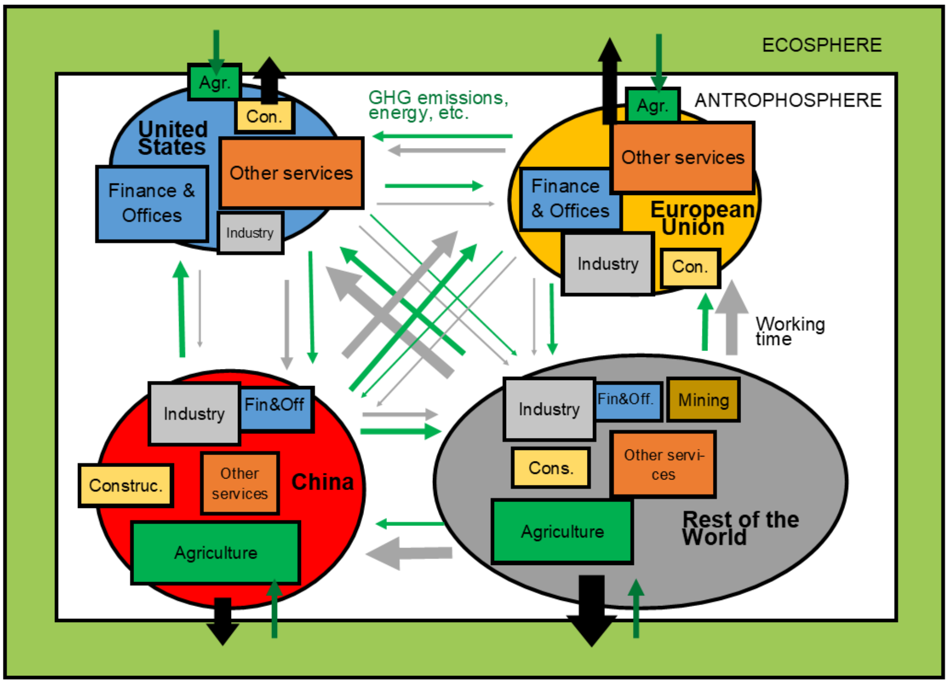


Figure 16 Functional specialization and the international division of labour are shown in different economic structures in the regions of the world.

Each region has different shares of economic sectors, which depend on the possibility of externalising functions and receive goods and services from abroad.

In the current globalized economy, paid work in national economies is entrenched in global production networks. Countries play different roles in the international division of labor, making them have different shares of sectors (Figure 16). For example, the EU has little employment in Agriculture due to mechanization and imports, whereas it allocates one of the largest shares in Offices.

Finance and offices carry out functions of control over the processes, be them monetary-financial, governmental, or even control production processes in industry and wholesale trade. Deindustrialization of developed countries involved a separation of management and production functions in industry. The externalization of manufacturing in the EU in many cases involved that the control of global production networks remained in headquarters in the EU. This functional specialization is reflected in concepts like “headquarter” and “factory” economies, coined by Baldwin and Robert-Nicoud (2014). The separation of management and design from industrial sectors has even generated ‘Factoryless Goods Producing Firms’, which are generally considered in the wholesale sector, for example Apple Inc. (Bernard and Fort, 2015). However, this geographical separation does not mean that deindustrialized countries do not consume goods anymore. Instead, they import them. The international division of labor and regional specialization have increased embodied resources and impacts in trade (Peters et al., 2011). Renner et al. (2020b) coined the term “cyborgization” to describe the increasing dependency on imports by foreign regions and external processes.

Different sectors along a production chain have different value-added capture power, which is related to the power of companies and countries over production and consumption chains. This uneven distribution of value by activity is summarized in the concept of the “smile curve” (Baldwin and Ito, 2021; Del Prete and Rungi, 2017; Rungi and Prete, 2018), where design, management functions capture more value-added than material extraction and transformation.

This unequal distribution of activities with different goods and bads among countries generates another type of classification: the core-periphery (Chang, 2002; Reinert, 2008; Wallerstein, 2011). Some countries allocate the activities that provide most profits and have control over the value chains, whereas others devote to the lower value-added and more labour-intensive ones. This generates an (ecological) unequal exchange (Dorninger et al., 2021; Hickel et al., 2022; Hornborg, 2003, 1998; Hornborg and Martinez-Alier, 2016; Martinez-Alier and Schlüpmann, 1987; Muradian et al., 2002).

This combination of factors makes that countries express different metabolic patterns according to their position in the core-periphery hierarchy and role within global value chains. In other words, they have different relative sizes of sectors and metabolic rates. This generates international dependencies and affects the national identity of countries. Velasco-Fernández et al. (2020b) show how the metabolic evolution of the EU and China in time reflect the European dependency of imports and the Chinese development and growth.

In chapter 5, we see how the embodied working time in trade is even proportionally larger than embodied GHG emissions. The imports in which the EU and US rely on influence the national employment structures. These foreign embodied inputs of working time enable them to have a shorter working week and a different allocation of time, towards services and longer education, which are typically associated with higher levels of development. Understanding these international dynamics is key for proposing new ways of organizing the economy.

3. Quantitative analysis

In this chapter, I explain more specific questions about quantitative analysis. In this dissertation, the main quantitative framework is MuSIASEM, based on the flow-fund scheme of Georgescu-Roegen and grounded on the concepts explained in chapters 1 and 2, among others.

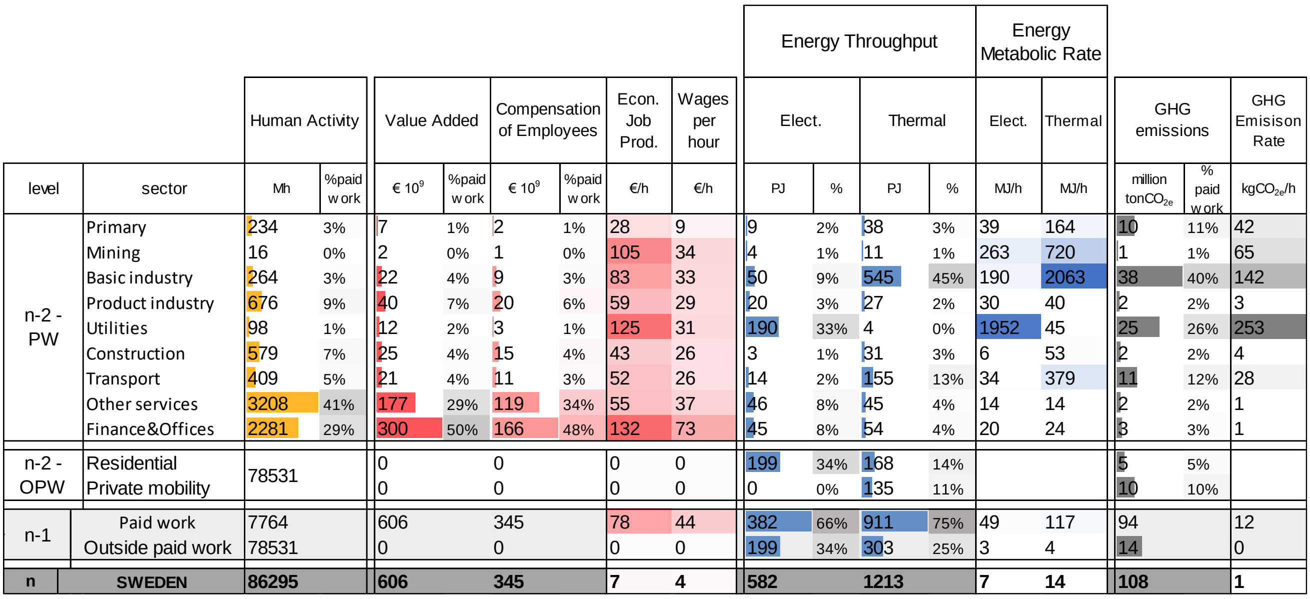
3.1. MuSIASEM

The Multi-Scale Integrated Accounting of Societal and Ecosystem Metabolism (MuSIASEM) is a system of accounting that has been specifically developed for studying the complex metabolic pattern of social-ecological systems at different hierarchical levels, scales and dimensions of analysis (economic, social, demographic, ecological, etc.) (Giampietro et al., 2013, 2012; Giampietro and Mayumi, 2000a, 2000b). MuSIASEM is based on the Georgescu-Roegen's flow-fund scheme (Giampietro et al., 2012), and it draws from a great amount of fields, some of them included in this introduction, such as non-equilibrium thermodynamics, complex system theory, participatory integrated assessment, post-normal science, biosemiotics, bioeconomics, theoretical ecology and practice theory. Despite using methodologies as well from industrial ecology in chapter 5, this is the main common theoretical framework in this dissertation.

It is a transdisciplinary approach to check the viability, feasibility, and desirability of society's current and projected metabolic patterns. It provides a quantitative representation of the metabolic pattern of the system under study in relation to three non-equivalent views: viability, feasibility and desirability. Viability refers to the functions expressed by the system with a suitable combination of structural elements capable of metabolising specific input flows in the anthroposphere. Feasibility is the compatibility with natural processes in the ecosphere (primary sources and sinks from the local environment and embodied in imports) (Ripa and Giampietro, 2017; Ripoll-Bosch and Giampietro, 2018). Desirability refers to compatibility with societal values, wants, regulations, etc.

The terms "technosphere" and "biosphere", commonly used in MuSIASEM and LCA, have been replaced with "anthroposphere" and "ecosphere" to reflect the fact that the anthroposphere encompasses not only technical but also symbolic and institutional aspects. Additionally, humans are part of the biosphere and rely on the processes that occur in ecosystems, which go beyond their biological components (e.g., a gold mine), hence the use of "ecosphere". This change in terminology was lucidly suggested by our colleague Ansel Renner.

The local end-use matrix describes the activities happening inside the boundaries of a system, such as a city, a country or a sector (Velasco-Fernández, 2017; Velasco-Fernández et al., 2020b, 2018). It keeps an accounting of variables of direct requirements (columns) of activities at different levels (rows). It provides a biophysical representation of inputs, outputs and capacity of sectors. This way, congruence constraints in the accounting can inform a biophysical budget discussion considering the different effects of conformation (relative size of the sectors) and performance (metabolic rates). This tool has been applied to study the metabolism of countries (Velasco-Fernández et al., 2020b), cities (Pérez-Sánchez et al., 2019), islands (Marcos-Valls et al., 2020), the residential sector (Chen et al., 2021; Pérez-Sánchez et al., 2022; Toboso-Chavero et al., 2021), and industries (Velasco-Fernández et al., 2020a, 2019).



										Energy Throughput				Energy Metabolic Rate				
		Human Activity		Value Added		Compensation of Employees		Econ. Job Prod.	Wages per hour	Elect.		Thermal		Elect.	Thermal	GHG emissions		GHG Emisison Rate
level	sector	Mh	%paid work	€ 10^9	%paid work	€ 10^9	%paid work	€/h	€/h	PJ	%	PJ	%	MJ/h	MJ/h	million $tonCO_{2e}$	% paid work	$kgCO_{2e}/h$
n-2 - PW	Primary	234	3%	7	1%	2	1%	28	9	9	2%	38	3%	39	164	10	11%	42
	Mining	16	0%	2	0%	1	0%	105	34	4	1%	11	1%	263	720	1	1%	65
	Basic industry	264	3%	22	4%	9	3%	83	33	50	9%	545	45%	190	2063	38	40%	142
	Product industry	676	9%	40	7%	20	6%	59	29	20	3%	27	2%	30	40	2	2%	3
	Utilities	98	1%	12	2%	3	1%	125	31	190	33%	4	0%	1952	45	25	26%	253
	Construction	579	7%	25	4%	15	4%	43	26	3	1%	31	3%	6	53	2	2%	4
	Transport	409	5%	21	4%	11	3%	52	26	14	2%	155	13%	34	379	11	12%	28
	Other services	3208	41%	177	29%	119	34%	55	37	46	8%	45	4%	14	14	2	2%	1
	Finance&Offices	2281	29%	300	50%	166	48%	132	73	45	8%	54	4%	20	24	3	3%	1
n-2 - OPW	Residential	78531		0		0		0	0	199	34%	168	14%			5	5%	
	Private mobility			0		0		0	0	0	0%	135	11%			10	10%	
n-1	Paid work	7764		606		345		78	44	382	66%	911	75%	49	117	94		12
	Outside paid work	78531		0		0		0	0	199	34%	303	25%	3	4	14		0
n	**SWEDEN**	**86295**		**606**		**345**		**7**	**4**	**582**		**1213**		**7**	**14**	**108**		**1**

Figure 17 End-use matrix of Sweden in 2015 at three different levels (n, n-1 and n-2).
Human activity and number of workers (Eurostat, 2019a)*. Value Added and compensation of employees* (Eurostat, 2019b). *Energy Throughput* (Eurostat, 2022a)*. GHG emissions, including emissions from biomass as a fuel* (Eurostat, 2021a).

The end-use matrix allows us to have a broad picture of the national metabolism of a country at a glimpse. Figure 17 shows the end-use matrix of Sweden in 2015 at different levels. There, we can see how *Other services* require most working time (41%) generating relatively lower Value added (29%) and compensation of employees (34%), with low direct energy carrier requirements (8% of electricity and 4% thermal) and GHG emissions (2%). The second sector that generates more employment is *Finance and offices* (29%), which generates at the same time most Value added (50%) and Compensation of employees (48%), with the highest economic job productivity (132€/h) and hourly wages (73€/h). On the other hand, *Basic industry*, with a 4% of working hours, is the sector generating more GHG emissions (40%) and requiring more thermal energy (45%), while generating rather low employment (3%) and value added (4%). We can see, as well, the totally different metabolic rates (EMRs and GHGER) of *Basic* and *Product industry,* with *Basic industry* being at one or two higher orders of magnitude than *Product industry*. *Utilities* include the generation of electricity and heat that is used by the rest of sectors, generating 26% of emissions. Electricity is rather low-emission in Sweden (nuclear, wind and hydro), whereas there are district heating systems where waste and biomass are burned. The residential sector used more electricity (34%) than the rest of economic activities.

The EUM can represent all the economic sectors in a country, as in the previous example, the same sector in different countries or time evolutions of sectors and countries. Given that sectors in national accounts follow relatively broad economic classifications like NACE Rev.2, we can find that a sector in two different countries has a totally different metabolism given the fact that they are performing different functions. This is further explored in the case of the automobile industry in chapter 6.

The EUM together with the analysis of the degree of openness enable us to characterize the viability of a given system. Openness through trade or migration represents a bonus of external viability and feasibility that relieves local limits and carrying capacity at expenses of curtailing foreign budgets. This is shown in chapter 5 with the examples of the EU, the US and China.

3.2. Flow-fund scheme

Funds are the basic structural elements of the economic process, determining the identity of the system that must be maintained in the period of analysis. Funds would be called factors of production in the classical school: Ricardian land, capital equipment and labour power (Georgescu-Roegen, 1983, 1971). They are the "*agents that perform the change*" in flows (Georgescu-Roegen, 1979, p. 1044). Georgescu-Roegen provides us with a different perspective to the objective of the economy, which is no longer to produce goods and services, but to reproduce in time the fund elements that provide them (Georgescu-Roegen, 1983; Mayumi and Tanikawa, 2012). This is what ultimately ensures a long-term sustainability of the economic system.

Funds are used to map the size of constituent components and are needed to contextualize the assessment of flows. For example, energy flows are expressed in relation to a specific category of human activity. Human activity defines the size of fund element metabolizing it. In this way, the intensive metabolic characteristics of the fund element can be defined, in this example, the Energy Metabolic Rate. The same can be done using land use as another type of fund – e.g., kg of wheat per hectare of land use, and total hectares of land uses in what production.

Flows cross the boundary of the process and are metabolized by the funds. They are either inputs or outputs to the process or system. These are, for example, GHG emissions, energy carriers, value added, water. Despite I am giving these examples defining some variables as funds or flows, their definition is in fact context dependent. For example, cars are a flow when we consider the yearly production in the automotive industry, whereas they are funds when we consider fleets: the power capacity available to provide mobility to a certain society in a given year. Another example would be trees, which are funds in the context of fruit tree agriculture, and flows in forestry for wood production (Farrell, 2021).

Both flows and funds must be included in a representation of a system in order to be complete (Georgescu-Roegen, 1971, 1970). In this dissertation, we are using the funds and flows listed in Table 1.

Table 1 Funds and flows of analysis in each case study in this dissertation

			CHAPTER 4	CHAPTER 5	CHAPTER 6
			Residential sector	Working time in trade	Automotive sector in the EU
Funds	Human activity	h	x	x	x
	Floor area	m^2	x		
	Power capacity	W	x		
Flows	Energy throughput	MJ		x	x
	GHG emissions	gCO_{2eq}			x
	Value added	€		x	x
	Salaries	€			x
	number of vehicles				x

In many other sustainability fields, the concept of stocks is often used instead of funds. Scholars unfamiliar with the fund-flow scheme usually ask what their difference is. Georgescu-Roegen (1983) suggests that the term ‘stock’ should be used for those elements that are not flows but do not maintain their identity, do not have metabolic characteristics and suffer from depletion – e.g. non-renewable resources - or filling – e.g. sinks no longer capable to process what is dumped in them, like the atmosphere with GHG.

3.2.1. Human activity

Time use is an overlooked variable for sustainability. Human activity is a fund element and therefore defines the size of society and is a limiting factor on the viability of a metabolic pattern. It is a limit at diverse levels: from the 24h/day of individuals to a national budget to a global viability limit that is embodied in international trade. This is the basic fund for the analyses carried out in this thesis.

Individuals and families in western countries feel the pressure of the 24h/day. This is due to many factors: the strong scheduling and working hours, increasing expectations of cultural and leisure activities, individualization trend of care activities, normalization of the extension of the area where daily life happens, etc. This pressure is not only given by the duration of activities, but also due to other temporal characteristics: synchronization, pace, scheduling, etc. In this dissertation, this side of time is explored in chapter 4 at the individual and family level, considering the time-geography implications and constraints.

Time use also sets a limit at the global level. The international division of labour has allowed nations to specialize in certain sectors, and for those with favourable terms of trade to reduce the amount of labour devoted to undesirable activities. This externalized work on undesirable activities is embodied in imported products, which have a lower cost of production in other regions (Alsamawi et al., 2014; Reinert, 2008). As time is a global limit in a given year, it suffers from a zero-sum game (Hornborg, 2009).This enlargement of the local budget of time in importing countries enables shifting working time to leisure and other cultural activities or transform the national economic structure towards more desirable economic activities for both society and workers, such as services (Pérez-Sánchez et al., 2021). Work is not important only for the utility of the production and service, but also because it provides means of living in society to workers and their families. Human activity in paid work is considered in chapter 5 (China-EU embodied working time in trade), chapter 6 (EUM auto industry).

3.2.2. Power capacity

Power capacity is defined as "the converters transforming energy flows at a given time rate" (Diaz-Maurin, 2016, p. 467): muscles, appliances, devices, vehicles and machinery. It is expressed in Watts. We can calculate energy consumption through power capacity, the efficiency of converters and their utilization factor (operating and capacity loads). In agriculture, a dramatic increase in power capacity has played a key role in intensification and industrialization. However, given the slow pace of natural processes (seasonality), machinery remains idle for long periods and time, translating into a low utilization factor. When power capacity is used in assembly lines in factories, its utilization factor increases. In fact, the objective is to minimize the idle time because machinery is an investment that can and must be amortised. Redundancies and standby time are reduced. This way, "*the economy of time reaches its maximum*" (Georgescu-Roegen, 1970, p. 6).

Paradoxically, power capacity in households it is not used with criteria of use maximization. Power capacity is owned at the individual or household level in order to have it available at all times to increase speed and flexibility of daily patterns. We all might have heard the now widespread idea that cars are only used 5% of the time, but this happens at one level or another with all kinds of household goods, from the stove to the drill. The amount of power capacity in households is in fact remarkable: stove, fridge, oven, waffle maker, TVs, computers, printer, hair iron, etc. The objective of industry is to produce as much as possible to maximise income. Therefore, the fact that each household has their own instead of sharing or renting them is pursued by the economic system. Moreover, planned obsolescence and the difficulty to repair make purchases more regular. This increases the emissions and other resource impacts in production.

The use of power capacity helps making a given activity with less time and effort. Owning the power capacity gives the possibility to perform activities anytime, making these time savings larger than when sharing or renting. The availability and use of power capacity are intrinsically linked to time use. This is further discussed in chapter 4, where the fund Power Capacity is further explored theoretically with its links to time use and energy in the exploration of the residential sector (Pérez-Sánchez et al., 2022).

3.2.3. Flow/fund relations

The existence of metabolized flows in MuSIASEM is always analyzed in relation to the fund elements metabolizing them. This flow/fund ratios quantify power, capacity, requirements, etc. that explain the expected metabolic characteristics of fund elements. Here, I explain the three main flow-fund indicators: Energy Metabolic Rate, Economic Job Productivity and hourly wages.

Energy Metabolic Rate

Nowadays, energy efficiency is considered one of the pillars of the sustainable future. This is defined as a lower input requirement of energy to produce the same output, service or function in order to decrease depletion of natural resources (not considering here the Jevons paradox). However, in fact, the efficiency that is central is the maximization of output per unit of time, speed and power. This takes the amount of input, and therefore conservation of resources, out of the picture. Time minimization and power maximisation accelerates activities and thus increases complexity in society (Giampietro et al., 1993; Giampietro and Mayumi, 1998; Mayumi, 1991). Similarly, Odum and Pinkerton (1955) define the *maximum power principle*, where the trend found in natural systems is applied to socio-ecological systems: "*there is a general tendency to sacrifice efficiency for more power output*." (Odum and Pinkerton, 1955, p. 331).

Since the industrial revolution and the use of ever larger amounts of exosomatic energy, the expansion of the use of energy carriers and power capacity has allowed us to liberate large amounts of human labour to perform an ever-larger number of activities with less effort. This exosomatic energy has substituted or complemented human labour. This way, human time and solar flows are not anymore the ultimate limiting factor of economic activity as it was in more traditional economies (Giampietro and Mayumi, 2000b, 1998). However, the productivity gains through the investment in machinery and automatization can increase in some sectors such as manufacturing, but in others such as services, it is very limited (Witt and Gross, 2020).

The large difference between energy use and the labour equivalent can be shown with the concept of "energy slaves" (Fisher, 2013; Taylor and Tainter, 2016). For example, Eve Fisher (2013) calculated that manufacturing a t-shirt in the Middle Ages with traditional manual tools, represented 579 hours of work. The metaphor of "energy slaves" illustrates the large amount of human work that is saved by the use of energy. Nevertheless, in fact, what the use of energy generates is multiplying the number of activities that we can perform without the limitation of human time and power. This has increased the complexity of society and generated time pressures in individuals.

These dynamics are explained by Harmut Rosa (2013, 2003), with his theory of social acceleration, which he defines either as a pillar or a characteristic of modernization. Three motors drive this acceleration: technological (compression of time and space through devices), structural (institutions such as family and work) and pace of life (feel hurried due to time pressure and stress). Georgescu-Roegen also reflects on this in his proposal of a Bioeconomic Programme. He asks society to change the mental framework that make us carry out activities faster, designing devices that enable this acceleration through time savings to perform even more activities (Carpintero, 2005; Georgescu-Roegen, 2017).

Therefore, what we find is that economic activity, more in industrial and primary sectors, is based on high use of energy carriers with machinery and relatively low amounts of work. This is reflected in the flow/fund ratio Energy Metabolic Rate: the throughput of energy carriers per hour of work in the end uses. The value of EMR is considered in MuSIASEM a proxy of the automatization and mechanization of the economy (Giampietro et al., 2012). Different economic activities have different EMRs by its own nature, such as metal forging and food industry. Moreover, the same activity can have different EMRs depending on the way it is carried out, for example, Low External Input Agriculture vs. High External Input Agriculture (industrialized monoculture).

Monetary rates

One of the most important outputs of production processes nowadays is income for the workers and value added for the economy. Their quantification is not determined by technological or physical characteristics, but by international economic and political dynamics which were briefly considered in section *2.5.2 Global production networks*. To analyse this, we have mainly two flow/fund ratios in euros per hour, the Economic Job Productivity and hourly wages.

- Economic Job Productivity: value added generated by hour of work.
- Hourly wages: salaries per hour of work.

3.3. Production recipes, substitutability, and dilemmas

When talking about production and systems, Georgescu-Roegen (1983, 1970) coined the term of production recipes. This is a different approach to that of production functions, such as Cobb-Douglas, where capital, technology and work are simply put into the same equation. Instead, production recipes describe the combination of funds, flows and instructions, where time plays a key role in terms of both temporal sequence and duration (Farrell and Mayumi, 2009).

As the same name indicates, these recipes have a parallelism to cooking. Recipes do not only involve a specific bundle of flows and funds, but a set of steps and a certain pace. The temporal dimension plays a role. Biofuels are a clear example. Whereas fossil fuels were created by natural and geological processes through millennia and now they are readily extractable by humans (stock-flow exploitation), we must generate this early production stage through agriculture and processing (fund-flow exploitation). This represents a waiting time for crops to grow, a temporal dimension that is unrelated to the hours of work. This is what happens in recipes as well. Sometimes the process involves waiting, for example, the time for the dough to rise to make bread.

Relations between production factors are fixed in a given production system. We know that the scarcity of one input limits the production of outputs. This is equivalent to the limitation of growth in plants being dictated by the scarcest resource, the Liebig's law of the minimum, developed by Carl Sprengel (1840). We could find a certain degree where substitution is possible within the same system. For example, most current diesel vehicles can use blends with biodiesel, or we could make pancakes with oat flour instead of wheat flour.

Many economists supporting green growth and weak sustainability believe that substitution of production factors is possible as a general rule. Even when the finiteness of resources is acknowledged, technological progress and elasticity of substitution are considered the tools to overcome scarcity (Dasgupta and Heal, 1974; Goeller and Weinberg, 1978; Nordhaus and Tobin, 1973). These arguments have been debunked by many authors in ecological economics (Daly, 1997b; Ehrlich, 1989; Mayumi et al., 1998).

There might be a certain flexibility of inputs and outputs where the system still works maintaining a similar system or object. Material science and selection already show us the limited substitutability and non-optimal quality of materials in a technical way. Material selection is an art of choosing the more adequate material, or the one whose drawbacks we can address or accept. It is possible that we require a material with specific mechanical, price, fire resistance, and fabrication characteristics, and we could make Ashby diagrams to explore candidates (Ashby, 2000). For example, we could substitute copper by aluminium for power transmission, but we will need much more aluminium for the same voltage. These trade-offs and compromise solutions are well known in engineering design of devices and structures, let alone when we analyse other kind of systems that include social and other incommensurable aspects.

Radical changes in inflows and outflows require changes in the structure of the system. The same product can be generated using different recipes, but their substitution depends on the change of funds. This change requires investments for the production in the case of power capacity. For example, we cannot run a diesel car with electricity, so we would need to produce electric cars. Another example is the infrastructure that is necessary for the energy transition to renewables. In terms of human activity, a return to a (more labour-intensive) non-mechanized agriculture could require employment to switch back from services to agriculture. The clearest limit is land use, where land uses for agriculture for food or natural areas would be needed to shift a from fossil fuels to biofuels.

I link those examples to the most representative variable, but in fact we will find changes in all dimensions as the complete bundle of inputs and outputs will change. For example, it is possible that in the short term while soils are not fully depleted and other inputs are available, a mechanized agriculture with large fertilizer inputs has a larger yield than a low-input agriculture. Therefore, not only more workers, but also more land use is required in low-input agriculture for generating the same output. Industrialized agriculture would require higher power capacity (machinery) and the subsequent flows (fuel, fertilizer, pesticides, etc.).

Infrastructure and machinery are fundamental structures, with large investments and investment cycles. As I've explained before, these can generate lock-in of future operational use, and, when the required inputs are not available, they can end-up as stranded assets. Since their lifetime is longer than the activities they take part, they tend to lock-in certain practices and production and to commit resources and emissions. Devices cannot be updated all at once when innovations irrupt. Generally, the transition is slow via substitution of older devices. An example is the electrification of the vehicle fleet.

The substitution of fund elements in the system generates two concomitant main changes: those related to the production of those fund elements (for example, factories for power capacity, education or culture for workers), and to the production of flows to operate those fund elements. This generates changes in the networks shown in Figure 15. These changes might get to anthroposphere limits related to the viability of the system. For example, it could be that a fast electrification of end-uses cannot be supplied by the current electricity system, or that a change in packaging from plastic to paper and cardboard puts a strain on the production capacity of pulp and paper industry. This viability limits can also as well derive from ecosphere limits, such as not having enough biomass production in forestry as a fundamental cause to the pulp and paper industry not being able to supply demand.

An ultimate non-substitutability of factors of production is determined by the biophysical limits of the Earth. We live in a full world nowadays, where power capacity is abundant, and the limitation is set by the natural capital, which is finite (Daly, 2005). Biophysical limits exist for all kinds of materials and other resources. Even if we could find substitutes, they could be already scarce or they could become scarce when these new uses are found and implemented. For example, we could change to a biobased economy until there is no more land left. Therefore, biomass production capacity might not be able to substitute fully the whole fossil-based output (materials, chemicals, energy carriers, etc.). Also, each addition of power capacity is providing a smaller marginal addition of output (Daly, 2005). Following the bioeconomy example, the last plots added for biomass production would likely come from a land use change of very low-productive marginal lands (or alternatively from very valuable natural areas).

The limits to substitutability are key to understand the existence of trade-offs and dilemmas. Academic literature and other documents often praise the existence of win-win solutions, and other concepts like co-benefits, multisolving, synergies, or even ecological transitions as an opportunity. Even though synergies might happen for certain dimensions, they also usually come with dilemmas and trade-offs. The link of flows and funds through metabolic ratios in production recipes implies that we cannot optimize all inputs to a production process. This is clear when we see critiques of the contradictory nature of the concept of sustainable development or the SDGs (Naredo, 2022; Scherer et al., 2018). These side-effects or dilemmas are even more challenging when they relate to two distinct systems, for example with operational and production impacts, or to the induced practices by the built environment on mobility.

These trade-offs and dilemmas are addressed in chapter 4, where we analyse qualitatively strategies for the sustainability of the residential sector.

CASE STUDIES

4. Factors and actions for the sustainability of the residential sector. The nexus of energy, materials, space, and time use.

The content of this chapter was published in Renewable and Sustainable Energy Reviews (Pérez-Sánchez et al., 2022)*. Minor changes have been introduced to the main text.*

4.1. Introduction

Dwellings are a central part of daily lives and where we spend most of our time. They represent a big share of the in-use material stocks, greenhouse gas emissions, and final energy carrier consumption (Huang et al., 2018; Södersten et al., 2020). These large impacts but at the same time essential function generate great policy interest in improving its sustainability. In the European Union, it has resulted in diverse directives and initiatives approaching mainly its technical side: the Renovation wave for Europe, the New European Bauhaus, and the Energy Performance of Buildings Directive.

This interest is also reflected in a large and growing literature. Many methods, scopes, and dimensions to analyze the housing stock or buildings coexist, which can be divided in broad terms into social sciences and engineering. Swan and Ugursal (2009) and Kavgic et al. (2010) reviewed and classified models for residential energy consumption and Langevin et al. (2020) updated Swan and Ugursal's classification. Even though each field irremediably includes aspects of the other, largely are only briefly mentioned, and truly interdisciplinary approaches are lacking.

Plain technological assessments assume given standardized needs. In many cases, they reduce the problem to the thermal performance. They analyze the artifact, i.e., the envelope and heating devices, but not its whole diversity of functions and contexts. Even though in most northern EU countries heating is the largest energy end-use in households, the functions and use of appliances become essential when analyzing sustainability and wellbeing. Governments and companies have put significant effort into decreasing energy use within the framework of technical energy efficiency. However, defining theoretically sound operational definitions of energy efficiency is not possible (Dunlop, 2019; Patterson, 1996; Velasco-Fernández et al., 2020a). One of the most common definitions is spending less energy on the same service. Generally, the definition of service is not questioned, overlooking alternative solutions to resource use reduction (Hagbert and Femenías, 2016; Shove, 2018). Yet existent technical solutions for sustainability are even acknowledged to be not enough (Cabrera Serrenho et al., 2019; Fossilfritt Sverige, 2018; Gutowski et al., 2013; Pauliuk et al., 2013b). Some models assessing housing stock development in time do include some social factors like occupancy or area per inhabitant. When they are included in models, these are generally more impactful changes than energy retrofits (Francart et al., 2018; International Resource Panel (IRP), 2020; Pauliuk et al., 2013b; Pauliuk and Heeren, 2020; Roca-Puigròs et al., 2020; Zhong et al., 2021), but the compatibility with social dynamics has not been fully assessed yet. Therefore, understanding what home is, its functions, and its relation to technical issues becomes essential.

On the other side, econometric models are the most commonly used approach the sustainability of the residential sector (Mata et al., 2021). Econometrical or agent-based analyses are grounded on rationality, giving centrality to price signals and individual behavior. Yet the voluntaristic change of consumer choices is constrained by the option space framed by society. Daily life is neither made by a set of discretional individual actions nor determined solely by infrastructure. Therefore, it depends on the organizational and institutional systems and hardware of wires, pipes, and power plants: practices are socially ordered (Shove et al., 2012). This means that daily life can be carried out in a variety of possible patterns of actions (McMeekin and Southerton, 2012). These must be coherent in their time use, family needs and duties, culture, existent infrastructure, and available external services.

Even though a case-by-case analysis of each building to assess its condition and possible refurbishment plays a key role, the mere sum of individual solutions will not necessarily increase sustainability. Solutions need to be scalable and coordinated in time and space. It is essential to have a broad overview of the combination of families (as institutions of meaning and competences, and as bodies with different characteristics) and dwelling stocks (technologies conformed by material elements heir to preterit practices). These systems have large inertia and thus changes are progressive. This large-scale perspective is useful for a variety of issues: the activities carried out by households and their insertion in daily lives, what should society do with existing housing, the need (or not) for its expansion, and how to maintain and build it.

It is not only the scale of analysis but also the multidimensional character of the residential sector that is important. When addressing sustainability issues and policy, it is unavoidable to face “wicked problems” (Rittel and Webber, 1973), in which many relevant perspectives and non-equivalent dimensions coexist. They should be considered simultaneously because there are incompatibilities between goals. This unavoidable existence of conflicting criteria of performance makes that there is no optimal answer to social problems. Only when considering both the large-scale and multidimensionality, transformative solutions can be proposed for a democratic discussion, acknowledging the possible trade-offs and uncertainties.

Mata et al. (2021) made a review of the most significant variables in models for energy and CO_2 emissions studied in the literature for the residential sector. Mata et al. (2022) made a review on non-technological and behavioral options for decarbonizing buildings. Hertwich et al. (2019) also listed a set of strategies in the framework of material efficiency for buildings. However, a truly integrative perspective to the diversity and trade-offs of variables from both social and technological approaches in the residential sector is lacking.

The objective of this chapter is to unravel the tight entanglement between social and technological issues in household metabolism and to explore possible actions for increasing sustainability of the residential sector. We analyze their trade-offs between a large variety of dimensions, focusing on the relation of the use of time, space, energy, and materials. To do so, we build on concepts from practice theory (Shove et al., 2012; Shove and Walker, 2014) and Multi-Scale Integrated Assessment System of Accounting (MuSIASEM) (Giampietro et al., 2012). Throughout the paper, we detail points to consider in the analysis and possible actions to increase sustainability belonging to: (i) changes of social practices (adopted by the households, but only if an appropriate context is available) and (ii) technological improvements (applied to structural elements associated with the dwellings). They are summarized in Table 2 and Table 3 (numbered for ease of reference in the body of the paper), including their effects on energy, greenhouse gas emissions, space, materials, time use, social organization, and desirability. Understanding these dynamics is essential to make plausible scenarios in models and effective policies.

We complement the explanations with data from Sweden and Spain in 2015. Sweden and Spain are both European countries but have significant differences in types of dwelling, income, and the organization of care (Daatland and Lowenstein, 2005), and thus in daily life patterns. Most of the included literature is referred to western countries. In this sense, ideas might be applicable to other contexts, but the analysis is centered in developed countries with a large amount of built environment and in this specific time in history. Homes have changed profoundly through the XXth century both in terms of size and types.

First, we define the residential sector as the combination of families or household units and dwellings. Afterwards, we explain the main dynamics of each of them in separate sections *Families or household units*, and *Housing*. Despite this organization in sections, it is impossible to isolate completely the topics since their dynamics are entangled and co-evolve. We analyze the members' composition and functions of families and put the focus on their time use patterns. Then, we present the housing stock, the social and technical issues affecting its use, performance, reproduction, and resource use. We also assess the economic role of the construction and real estate sectors. Finally, we present the main conclusions.

4.2. The residential sector

The residential sector is a central part of societal dynamics and of the daily life of people. In modern societies, it could be concisely defined as the sector complementary to paid work and the market economy that is responsible for the reproduction of society, as shown in Figure 18. However, this is a very simplified view. The residential sector is the combination of families/household units (of organized individuals) and dwellings (within municipalities/urban forms), whose functions adapt with the surrounding informal and formal sectors in paid work. This continuous adjustment makes the boundary definition and energy accounting more challenging. What happens in dwellings and home is variable and coevolves with the material arrangements and daily practices. It has changed through history (Rybczynski, 1987; Schwartz Cowan, 1985) and the concept is described differently among disciplines (Ellsworth-Krebs et al., 2015; Mallett, 2004). In short, we can say that it is not only a place of rest and leisure but also of (mostly unpaid) work and a centre of organization of daily life and social reproduction. In dwellings, people carry out an extensive array of activities, including:

- Sleeping and rest
- Cooking (food management and cooking, washing dishes) and eating
- Personal care (showering, dressing up, etc.)
- Clothing care (washing clothes, ironing, drying, etc.)
- Leisure (reading, TV, computer, hobbies, social interaction, etc.)
- Caring for others (helping children with homework, helping with personal care, etc.)
- Telework and other kinds of work (workshops, agriculture, etc.)

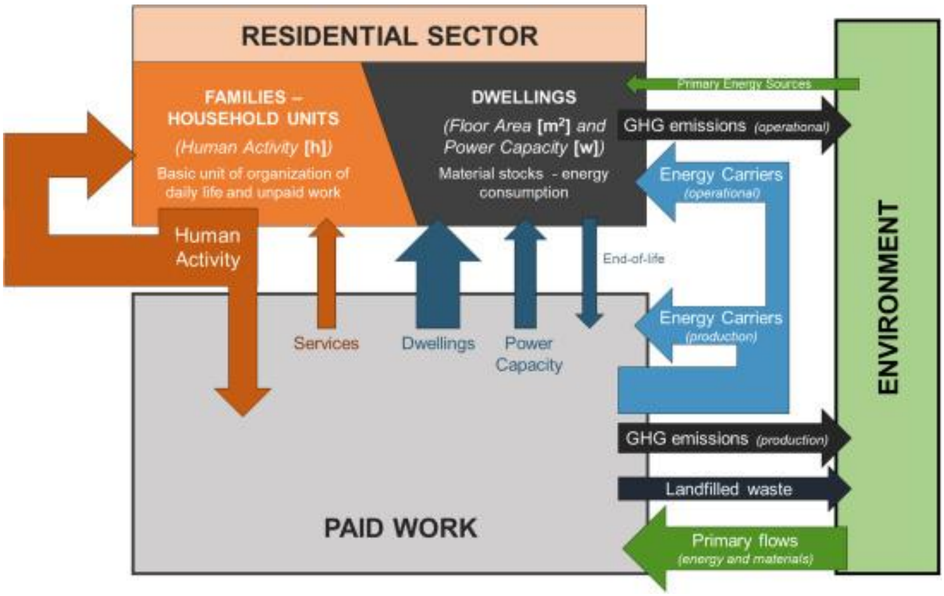


Figure 18 The two parts of the residential sector (household units and dwellings) and simplified key flows from Paid Work and the Environment.

The segmentation of “domestic” resource use does not adequately address modern life practices (Hagbert, 2016). The residential sector is connected and interdependent with many other sectors to which can leak activities and their concomitant resource use. For example, food can be provided by cooking at home with diverse levels of support of processed products from the food industry, home delivery or by going to a restaurant. This means that functions that could be found within families in a type of society, can be collectivised or marketed partially or entirely in others.

These are especially important in the domain of unpaid work: food provisioning, care centres for the elderly and children, laundry, etc. For example, a couple with children could follow a male breadwinner model, where all reproduction tasks are carried out unpaid by the stay-at-home mother: cooking, cleaning, care, etc. On the other hand, a young professional may live on his own in a small flat. This professional works long hours, always eats out, contracts a worker for housekeeping, and even showers at the gym. In this case, all household services are marketed, and the dwelling is basically a place to store and sleep when he is in town. As a result, much of the expected residential energy consumption is shifted to service sectors. Setting the boundary of the household sector is thus challenging and not universal.

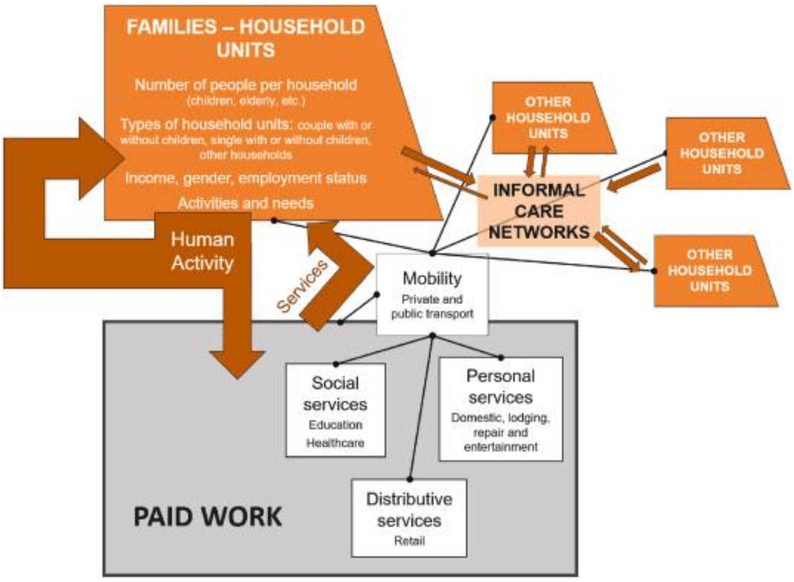


Figure 19 Household units and their relation to services in paid work and informal care networks. Human Activity is provided from household units to paid work through employment and a share returns in the form of services to households. Some human activity goes to informal care networks, where different household units (community, friends or extended family) provide services in a reciprocal mode/unpaid work. These relations generally require mobility to take place. Classification of paid work services to people from (Schettkat and Yocarini, 2006)

In this sense, families rely on a large variety of out of home support systems, which could be classified as non-formal (work groups, church, etc.), informal (extended family, neighbours, extended kin), and formal (school, health agencies, protective agencies, welfare agencies) (Andrews et al., 1980) (see Figure 19). Although the dichotomy shown in Figure 18 between paid work and households may be too strict since there are other elements outside paid work, it is becoming a reality in countries like Sweden. There, the loss of informal care networks is compensated by a large state formal support within paid work (Nyberg, 2012), whereas Spain still relies largely on the extended family.

The individualisation of life and the loss of social interaction based on streets and neighbourhoods broke down the balance of family life and the collective (Ariès, 2018; Jacobs, 1961; Mouratidis, 2018). In part, this can be explained by the hypermobile society (Adams, 2001), which separates people from the area close to home by means of the universalisation of the private vehicle and other transport modes. The area and social network of daily life can be larger at the expense of being weaker.

This is important since home is a “pocket of local order”, where daily life starts and ends (Ellegård and Vilhelmson, 2004). The functions allocated to home, duties and expectations of activities, the form of dwellings and the rest of buildings where life happens will define time pressures and energy consumption in mobility. The set of dwellings plus other buildings form municipalities with specific urban forms and define accessibility to services, goods, and work through daily mobility (from a short walk to a long car drive) (Figure 20). Metropolitan cities allocate the largest amount and variety of services, but rural areas are essential in their functions of the management of biomass and mineral flows and ecosystems. Compact urban forms that comprise multi-dwelling buildings generate higher densities of demand. In consequence, they make viable services such as retail and education and centralise water, energy, internet, transport, and waste infrastructure (Couch et al., 2006; Ewing, 1994). Proximity and vitality, among others, enable active mobility and thus potentially decrease energy use and GHG emissions in mobility (Delclòs-Alió and Miralles-Guasch, 2018; Gómez-Varo et al., 2022; Jacobs, 1961). Single-family houses allow a life a priori closer to green areas, but the generalisation of this model in suburban sprawl occupies large extensions of Land Use, increasing the distance to services and work. This entails a dependency on the private car for the most basic daily needs, overriding the initial individual benefits (Bastos et al., 2016; Hayden, 1984; Sheller and Urry, 2006). Single-family houses are thus private goods (Hirsch, 1977) that can provide benefits to a certain limited amount of people, but lose their intrinsic characteristics when they are extensively put into practice. Therefore, both the type of dwelling and the emerging context play a role in time and energy use in transport (Anderson et al., 2015; Bastos et al., 2016; Nichols and Kockelman, 2014).

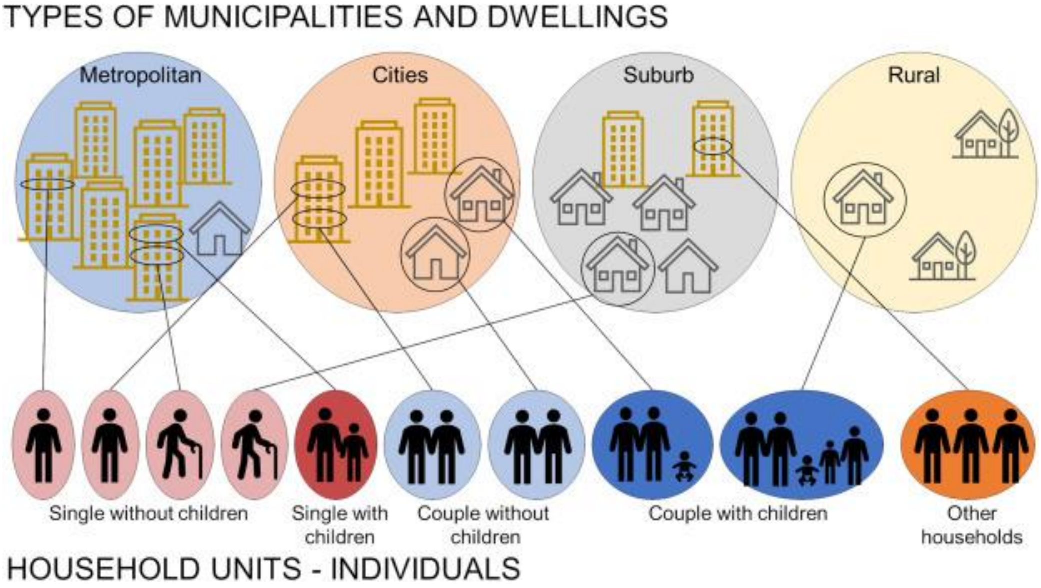
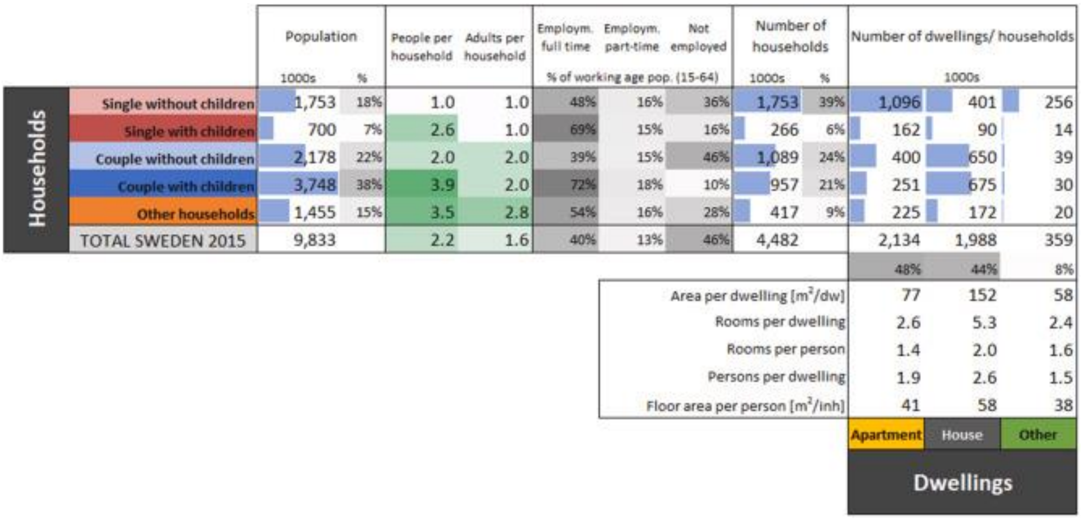


Figure 20 The residential sector is formed by organized individuals in families that live in dwellings, which are located in and generate different types of municipality, affecting their access to services and paid work.

In general, each family or household unit lives in a dwelling, but there are other housing options (retirement homes, student dorms, jails, etc.). Households may have more than one residence for example for specific periods of time (e.g., holidays) or might have problems affording even one. Here we only account for dwellings in use, but there is always a share of unused housing.

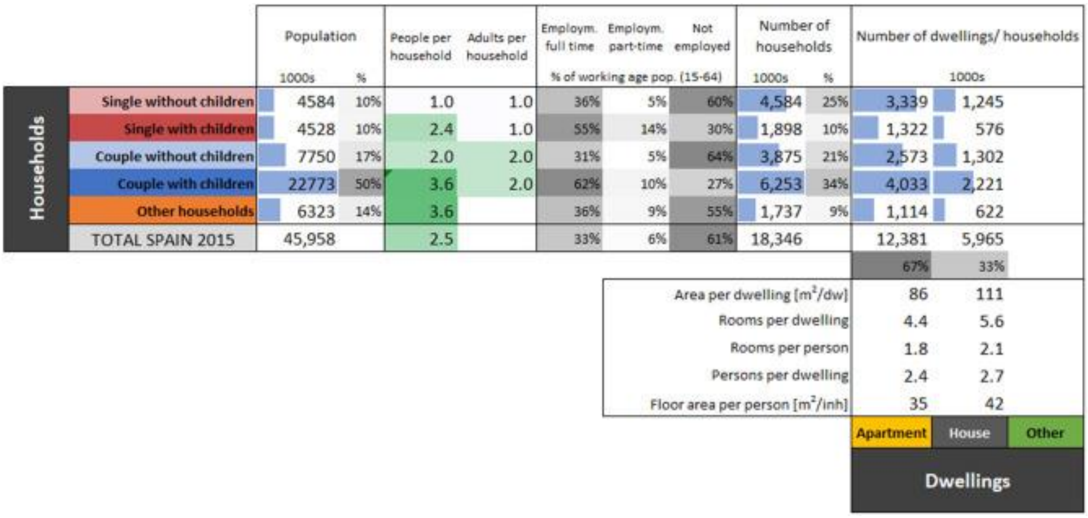
Figure 21 and Figure 22 show an overview of the organisation of types of household units in types of dwelling in 2015 in Sweden and Spain, respectively. In Spain, the housing stock is mainly composed of apartments (67%), whereas in Sweden, the percentage is smaller (48%). In Sweden, there is a strong distinction between the uses of apartments and houses. There, most single people live in apartments, while houses are occupied by couples and couples with children. In the case of Spain, all types of households live more often in apartments, whose size is larger (86 m^2/dwelling compared to 77 m^2/dwelling in Sweden). The Swedish stock of apartments was designed more for one-person households, whereas apartments are common in Mediterranean countries for larger families.



		Population		People per household	Adults per household	Employm. full time	Employm. part-time	Not employed	Number of households		Number of dwellings/ households		
		1000s	%			% of working age pop. (15-64)			1000s	%	1000s		
Households	Single without children	1,753	18%	1.0	1.0	48%	16%	36%	1,753	39%	1,096	401	256
	Single with children	700	7%	2.6	1.0	69%	15%	16%	266	6%	162	90	14
	Couple without children	2,178	22%	2.0	2.0	39%	15%	46%	1,089	24%	400	650	39
	Couple with children	3,748	38%	3.9	2.0	72%	18%	10%	957	21%	251	675	30
	Other households	1,455	15%	3.5	2.8	54%	16%	28%	417	9%	225	172	20
	TOTAL SWEDEN 2015	9,833		2.2	1.6	40%	13%	46%	4,482		2,134	1,988	359
											48%	44%	8%
										Area per dwelling [m²/dw]	77	152	58
										Rooms per dwelling	2.6	5.3	2.4
										Rooms per person	1.4	2.0	1.6
										Persons per dwelling	1.9	2.6	1.5
										Floor area per person [m²/inh]	41	58	38
											Apartment	House	Other
											Dwellings		

Figure 21 Combination of types of household and dwelling in Sweden 2015.

Data: number of people (Statistics Sweden, 2020a) *and households* (Statistics Sweden, 2020b), *employment* (Eurostat, 2015)*, area per dwelling* (Statistics Sweden, 2020c)*, rooms per person* (Eurostat, 2020a)



		Population		People per household	Adults per household	Employm. full time	Employm. part-time	Not employed	Number of households		Number of dwellings/ households		
		1000s	%			% of working age pop. (15-64)			1000s	%	1000s		
Households	Single without children	4584	10%	1.0	1.0	36%	5%	60%	4,584	25%	3,339	1,245	
	Single with children	4528	10%	2.4	1.0	55%	14%	30%	1,898	10%	1,322	576	
	Couple without children	7750	17%	2.0	2.0	31%	5%	64%	3,875	21%	2,573	1,302	
	Couple with children	22773	50%	3.6	2.0	62%	10%	27%	6,253	34%	4,033	2,221	
	Other households	6323	14%	3.6		36%	9%	55%	1,737	9%	1,114	622	
	TOTAL SPAIN 2015	45,958		2.5		33%	6%	61%	18,346		12,381	5,965	
											67%	33%	
										Area per dwelling [m²/dw]	86	111	
										Rooms per dwelling	4.4	5.6	
										Rooms per person	1.8	2.1	
										Persons per dwelling	2.4	2.7	
										Floor area per person [m²/inh]	35	42	
											Apartment	House	Other
											Dwellings		

Figure 22 Combination of types of household and dwelling in Spain 2015.

Data: number of people and households (INE, 2015) (Statistics Sweden, 2020b)*, employment* (Eurostat, 2015)*, area per dwelling* (Entranze project, 2013) *, rooms per person* (Eurostat, 2020a) *. No data for "other" type of dwelling.*

Both demographic structures and the built environment have large inertia and change only gradually. This generates a strong lock-in effect. An incompatibility of dwellings and household units will require adaptation of housing in terms of layouts or number, or of expectations and practices. Otherwise, this could result in overcrowding or under-occupation. Akrich (1992) coined the term “scripting”, the framework of action that technical objects define. In the case of dwellings, they embody a type of family/household occupants and of expected functions. For example, an apartment with three bedrooms, one of a larger size, would be adapted to a family of a couple and two children. This hierarchy of bedrooms or a one-room apartment would not be fitted for a household unit of three single adults (Muxí Martínez et al., 2009). These combinations could not be desirable but could still technically work out.

4.2.1. The funds in the residential sector

Human Activity is a central variable of the social side of the residential sector: household units, who must manage their budget of time to fulfill their needs and duties. On the other hand, the most technological side of the residential sector (dwellings) is defined by Floor Area and Power Capacity. As we will see in the next sections, these dimensions are in fact connected.

When we talk of dwellings, we do not refer to a static monolithic structure. They consist of different parts or layers of different levels of flexibility and lifetimes (site, structure, skin, services, space plan, and stuff) (Brand, 1995; Durmisevic, 2006). Here we divide them into the two main funds, considering their broad functions and partaking artifacts: Floor Area and Power Capacity. The structure and envelope of buildings define Floor Area (in m^2) and are built in the construction sector (section *4.4.5 Construction and real estate sectors*). Floor Area is a key variable for desirability and resource uses (materials, land use, energy, GHG emissions, etc.). Dwellings are full of an ever-increasing number and variety of appliances that carry out functions and/or reduce the required time and effort to perform them by metabolizing energy carriers, the Power Capacity (in W) (Diaz-Maurin, 2016). The size, access, and use of these funds are key to understanding the performance of the residential sector.

4.3. Families or household units

There are different types of families or household units: one-person households, cohabiting couples, diverse types of families with children (single parents, nuclear family model, or more extended alternatives), and other types without family ties, for example, student flats. The latter may not coordinate activities like cooking so much. The organization in household units is dynamic in time throughout life, namely the family life cycle or life-course trajectories (Du and Kamakura, 2006). People play different roles in different kinds of households along their lifetimes but also in communities and employment. These roles (carer, employee, friend, son, etc.) define the possible patterns of their daily lives and are reflected in their time use. Therefore, they are not mere individuals acting by their own interests and criteria. Their autonomy is limited. As family members, they participate in the organization and duties and/or receive care from others in different reciprocal ways (Bubolz, 2001; Sahlins, 1972). Within the domestic sphere, unpaid work done by women still plays a central role (Hammer et al., 2020; Istenič et al., 2019; Moreno-Colom, 2015; Rentería et al., 2016). This is important because it forces women to have a double shift (increasing time pressures) or to renounce fully or partially to paid employment, making them dependent on their partners.

The family distribution by age in Sweden in 2015 is shown in Figure 23. At least half of the Swedish population between 31 and 53 years old lived with their children. The most frequent type of family with children are nuclear families with two parents, also with the largest average household size, almost 4. It only represents 21% of the households in Sweden. In Figure 23, there is the demographic structure of Spain in 2015 by type of family. In this case, the share of the population in the family type “cohabiting with children” is larger (50% in Spain vs 38% in Sweden), mostly at expense of single and couple households (see Figure 19).

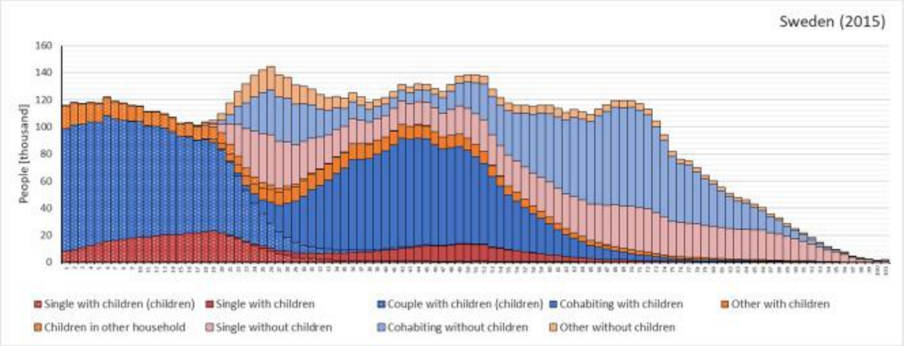


Figure 23 Demographic structure of the population of Sweden in 2015 by type of household and role (adults vs children).

Data from Statistics Sweden (2020a).

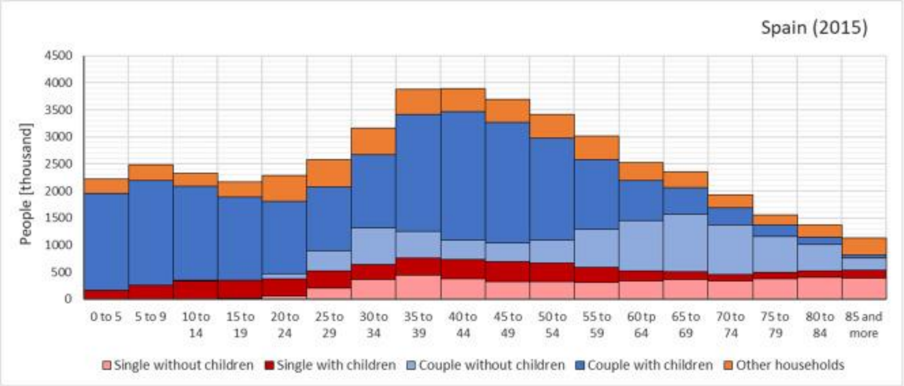


Figure 24 Demographic structure of the population of Spain in 2015 by type of household.

Data from INE (2015)

In Sweden, as in other developed countries, women live on average longer than men and usually end up living by themselves. Few people live in retirement homes or with their adult children. The large shares of elderly living alone and of early emancipation from parental home define a short time of nuclear family with a household size larger than 2 people. Half of the people by 22 have left the parental home, a younger age than in other EU countries. This translates into a large share of one-person households (39%) compared to other EU countries, for example, Spain (25%). Changing these deeply rooted values of independence and autonomy is not easy, but these heavily affect resource consumption. Sweden is a telling example of families choosing their dwellings to accommodate expected “peak household” moments (Ellsworth-Krebs et al., 2019). The prevision of young couples of having children and the subsequent “empty nests” years after results in an overkill: an under-occupancy of the nuclear family houses for long periods of time. In turn, there is a larger demand for housing for independent young people.

The combination of all these types of families makes that Sweden has an average household size of 2 persons, similar to Denmark or Germany, but a very low value compared to other countries such as Spain (2.5) (Eurostat, 2022b, 2020b), a value even higher than Sweden in 1980 (2.4) (Popenoe, 1987). Both are far away from Spain in 1958 (4.5) (González de Molina et al., 2019). While in the last decades, household size has generally fallen all around the world, European and North American households are still way smaller than those in developing countries (e.g., Colombia 3.53 or Chad 5.78 in

2015) (United Nations. Deparment of Economic and Social Affairs. Population Division., 2019).

This specific societal organisation with small household units decreases internal coordination requirements within households but entails external support for care needs of children, elderly, and disabled people and larger material resources, both in area per person, energy, and power capacity (i.e., appliances and devices). In market economies and depending on the welfare state type, the external support depends heavily on the purchasing power and the choices defined by the market. What is more, the individualization of life generates loneliness, impacting health (Klinenberg, 2016). Considering all these drawbacks, we could make a thought experiment: if all adult single people in Sweden would live with another person, Sweden would need 26% fewer apartments and 10% fewer houses. We could assume an equivalent reduction in energy consumption in heating and common appliances (e.g., fridges) and a certain reduction in other types of energy consumption (cooking, lighting, etc.). Yet there is a crucial question: Would Swedish citizens consider that to be an acceptable solution?

4.3.1. Human activity and social organisation

In Georgescu-Roegen's fund-flow scheme (Georgescu-Roegen, 1971, 1970), where MuSIASEM is grounded, time is considered a fund: Human activity associated with the physical existence of human beings (Giampietro et al., 2012). Families reproduce human activity physically by raising children and maintain it by means of care activities. Although the residential sector is the central actor, there are also activities in services within paid work that take part in the reproduction of the fund Human Activity, for example, education and healthcare (Figure 19).

Human time is one of the key but rather overlooked variables in sustainability, albeit it is required for all activities. Some residential energy models have already recognized the role of time use and have made it the central variable (D’Alisa and Cattaneo, 2013; De Lauretis et al., 2017; Jalas and Juntunen, 2015; Lőrincz et al., 2021; Ramos-Martín et al., 2009; Sekar et al., 2018; Widén et al., 2012; Widén and Wäckelgård, 2010). People can already generally acknowledge the centrality of time in their lives. We feel the pressure and hurriedness of the 24 h/day in our daily life, even more on weekdays (Southerton, 2003). People and families organize the allocation of their time considering all constraints and activities in and outside the home. In this sense, duration is not the only important aspect, but also other many dimensions of time, such as synchronization, sequence, and rate, among others (Parkes and Thrift, 1975). The hourly and daily organization is defined by coupling with others and by authority constraints (Parkes and Thrift, 1975). In this sense, paid work and family care play key roles in the organization of daily life and generate great temporal constraints. This shows the limited autonomy and choice of the individual.

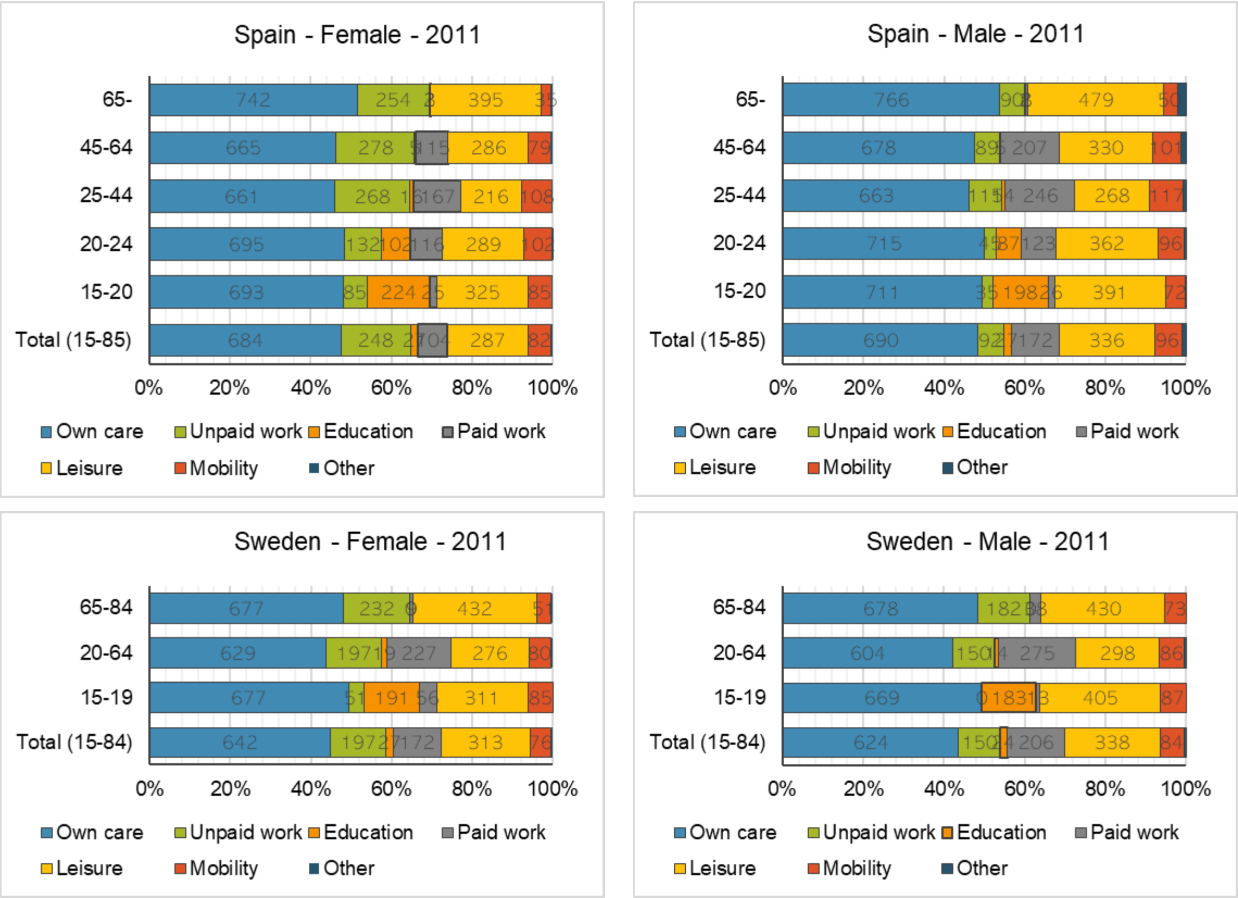


Figure 25 Time use patterns of Females and Males in Spain and Sweden in 2011.
Source data: Time use surveys in Spain (Eurostat, 2019c) *and Sweden* (Statistics Sweden, 2016).

As an example of distribution of amounts of time, we can see the time use patterns of males and females in Sweden and Spain in 2011 (Figure 25). For the selection of categories, see appendix *9.1*. We analyse the age intervals 20-64 for Sweden and 25-44 in Spain because these are those with largest contribution to paid work and in many cases, these are combined with care of children. This is shown by the fact that these are the intervals with the least *own care* and *leisure*. This picture of time pressures from 2011 can be put in the context of the loss of sleep time in Spain, where the average Spanish person has lost almost 25 min of sleep a day from 1987 until 2011 (FUHEM, 2023). In Sweden in 2011, they get more *paid work*, less *unpaid work* and less *own care* (*own care* includes sleeping) and mobility compared to Spain. Spain shows larger differences by sex than Sweden: women participate less in Paid work and Leisure and more in Unpaid work.

There are some strategies that can be followed in order to save time (Nickols and Fox, 1983; Strober and Weinberg, 1980). These go beyond the residential sector. To make more of the day and ease the time burden, people (i) use Power Capacity and energy, (ii) decrease their expectations on quality or quantity of activities, (iii) increase the household size, (iv) buy services in the market or use public services, (v) or collectivize activities outside the household.

These strategies have impacts as well on the material dimensions, listed in Table 3. For decreasing GHG emissions and energy use, the first strategy, using Power Capacity for time compression, should be reversed, considering always the impacts in time use and daily patterns. Therefore, in order to improve the energy performance and sustainability of the residential sector in a broader sense, we could shift the usual framework of technological change to that of social innovation (Gershuny, 1987; Nelson and Allwood, 2021). For this approach to succeed, desirability plays a significant role. Citizens must accept the social conditions of these alternative arrangements to provide the subsequent benefits in terms of environmental feasibility and social viability (Ripa and Giampietro, 2017; Saltelli and Giampietro, 2017).

Decrease use of Power Capacity

There is a trade-off or nexus between the fund Human Activity and energy. Some Power Capacity allows to carry out activities with less time and effort by the use of energy, defined as time-saving technology (Bowden and Offer, 1994). In contrast, time-using technology would enhance the perceived quality or allow different kinds of leisure, for example the TV. This generates an energy-time nexus, quantified in the MuSIASEM framework with the Energy Metabolic Rate [MJ/h], which defines the amount of energy per human activity (Giampietro et al., 2014, 2012).

The availability of technology makes that more activities can be performed in the same time, potentially generating a time rebound. Ecological changes in lifestyle such as moving by public transport instead of a private vehicle could be considered “time investments in the environment” (Rinderspacher, 1996) (strategy 2.1 in Table 3). These investments are, in many cases, not individually possible without certain waivers, or not universally possible, and therefore only generalisable through societal change. For example, living without a car in the many areas of the US is not possible due to the sprawl urbanism, the lack of public transport and/or services and jobs close to homes. Social and infrastructure changes to allow making these time investments and depend less on energy-consuming power capacity, are the precondition for time wealth (*Zeitwohlstand*) (Reisch, 2001; von Jorck et al., 2019). This is considered key to a more sustainable life and includes sufficient time, plannability, synchronization, and sovereignty (Geiger et al., 2021; von Jorck et al., 2019).

This all-rounder outlook of time is important because the operation of appliances is not always only directly related to duration. For example, fridges and freezers work continuously to preserve food. They affect food provisioning by reducing the frequency of trips to buy groceries and allowing the consumption of otherwise perishable foods, for example dairy or cooked food. Through innovation, the technical object might use less energy by volume of stored food. But this might make people use larger freezers in order to reduce the number of trips to supermarkets or to avoid planning meals, backfiring the relative efficiency per unit of food (Shove and Southerton, 2000).

Decrease quantity or quality of activities and provide flexibility

The increasing energy use and power capacity ownership is the current main strategy to overcome the daily personal and family budgets of time. The availability of technology has raised the expectations of the quality or quantity of activities carried out during the day and it the end normalized the ownership of certain Power Capacity and activities. This has accelerated the pace of life and compressed activities, reducing the pauses between activities or increasing multitasking (Rosa, 2003; Wajcman, 2008). For example, the existence of washing machines has not reduced the time in this activity due to the increased frequency linked to the higher standards of cleanliness. Some authors state instead that the time pressure in modern societies is closely related to a middle-class expectation of levels of leisure (Gershuny, 1992; Gershuny et al., 2019). The gender differences related to care work and double shifts also play a key role (Abio et al., 2019; Sullivan and Gershuny, 2018; Wajcman, 2008).

Therefore, to ease the strain on the time budget, the number, time, and quality of activities could decrease (strategy 1.5 in Table 2). For example, due to the time in childcare, parents of young children opt for more part-time jobs or staying at home (at expenses of income dependency), for a job closer to home so mobility is reduced, or could have fewer sleep hours, affecting their health and wellbeing.

In the specific example of quitting a job in the family unit or relying on extended family members without a job, this does not only entail a liberation of a quantity of time, but also it would give flexibility to the family time budget (strategy 1.6 in Table 2). Both childcare and paid work have generally strict scheduling which may be difficult to make compatible. It must be taken into account that it is women that normally take this role nowadays and that we could find alternatives to address this inequality while providing flexibility.

Shareability and economies of scale

Furthermore, we could make further deeper structural changes in the mode of provision to yield economies of scale by decreasing the labour and resources per person. These are increasing size and organization within households, building communities, and providing services in paid work. Most of these strategies run counter to the current individualization trend. These social innovations require a broader analysis of the needs and how they are provisioned. For example, stay-at-home parents and kindergartens are two ways of coping with childcare, and people can cook at home, or alternatively, they can enjoy the service in a restaurant or canteen.

Sharing a dwelling and its activities (strategy 1.1) requires negotiation, coordination, and commitment with more people, but at expense of overall lower resource use and duration of tasks. Literature shows that larger household units use fewer resources per capita (Isaksson and Ellegård, 2015; Ivanova and Büchs, 2022), for example, energy in Denmark (Gram-Hanssen, 2013), energy in Australia (Ironmonger et al., 1995), water in 4 European countries (Richter and Stamminger, 2012), and energy and carbon footprints in EU countries (Ivanova and Büchs, 2020). When sharing is not voluntary but by necessity and not built around a household organization of tasks, it may backfire the expected savings (e.g. see Klocker et al. (2012)).

Nowadays, only 9% of the households in Sweden and Spain (Figure 21 and Figure 22) are “other households” (about 3.5 inhabitants per dwelling). These household types different from the strict nuclear family or one-person households could be extended family or peer-shared types. This arrangement might not be currently desired by citizens, but the only way compatible with their economic and/or care situation. To become a compelling alternative, it requires the establishment of rituals, negotiation and conflict resolution, and a revision of power dynamics within families.

Taking a further step, there are examples in the whole reorganization of space and activities in larger units or with collective areas in the residential sector under different names: cohousing, collaborative housing, coliving, communal housing, or collective housing (Francart et al., 2020; Lorek and Spangenberg, 2019; Tummers, 2016; Vestbro, 2012), also specific for older people including or not care and support services (Hughes, 2012; Sutherland, 2011), and historical examples such as the history of collective housing considering reproduction work (Hayden, 1981) or apartments with collective housekeeping services in New York at the end of the XIXth century (Puigjaner, 2014).

In this kind of larger collective organization, the coordination takes a higher level with external management and/or regular meetings and working groups (Francart et al., 2020; Girbés-Peco et al., 2020). Yet energy or greenhouse gas emissions savings associated with these solutions have not been studied enough (Tummers, 2016). The existent power capacity and infrastructure does not match the needs of these alternative modes, which would include shared or public spaces and larger and sturdier common appliances.

Neighborhood organizations, the market or the government can support specific functions which are traditionally associated with households, such as public kitchens or canteens, daycare centers, laundromats, or tool libraries (strategy 1.2).

Some of these strategies are framed with the concepts of product-service systems, where the objective of companies is not to sell products anymore but to enable ownerless consumption of goods, or to offer the services that those products provide (Mont, 2004; Tukker, 2015, 2004). However, these collectively provided services are only viable if people are willing to do them as unpaid work for the community or if companies can sustain wages for their workers. The viability of waged employment is one of the main challenges raised by product-service literature (Mont, 2004; Tukker, 2015, 2004). It also entails a complete transformation in the companies' structure and functioning (Tukker, 2015).

To some extent for some sectors, this shifting to paid work has already been implemented related to welfare state. While in Sweden jobs in education, health and other care are common in the public sector, Spain does not have such broad public support, and extended families play a great role in child and elderly care. Also, wage workers usually carry out more specialized tasks and can invest in their education and improve the quality of the service, whereas within households, adult members must carry out a large variety of activities. For example, in terms of food provisioning, professionalization could improve logistics (e.g., reducing food waste and packaging), and fulfill societal expectations of quality and healthy eating, instead of laying the burden on individuals and families. Yet collectivization could entail the loss of the cultural load and intimacy of house and care work made by families (mostly women).

These changes in social organization and the function of the household can lead to radical changes in the layout of dwellings as we understand them now, for example with kitchenless homes if they take cooperative housekeeping to the maximum level (Hayden, 1981, 1978; Muxí Martínez, 2018). The changes in layouts and the existence of less privative space for the benefit of communal spaces with economies of scale can be also in relation to leisure and social interaction (Fernández Gutiérrez et al., 2021). This transforms the dwelling into a multi-scale space (privative and communal), opening the definition of the household and including the community.

The expected functions and form of dwellings can be adapted in relation to the services provided by its context in paid work. For example, what is considered a paradigmatic example of a minimum dwelling, Le Corbusier's *Cabanon de vacances* (13.4 m^2), does not include a shower and kitchen. This small size is possible due to its location, adjacent to a restaurant, and surrounded by a large natural area, including a beach.

Demand response

The electricity mix is a key variable regarding indirect impacts from electricity end uses in buildings (Francart et al., 2018; Heeren et al., 2015). The intermittency of the ever-increasing share of renewables in the mix could make that the national or domestic electricity systems cannot adapt anymore to demand at all times as it does now in developed countries.

This change for sustainability forced by the energy system also affects daily practices. Demand response strategies aim to shift activities in the everyday activity context or via smart systems. On the one hand, daily practices might have to change actively by users, requiring flexibility from the rest of activities to adapt to the price signals (related to strategy 1.6) (Adams et al., 2021; Gram-Hanssen et al., 2020; Higginson et al., 2014; Torriti, 2017; Torriti et al., 2015). On the other hand, electronics and smart systems (strategy 2.2) allow the disconnection between functioning of appliances and the presence of users (for example with programmed laundry and heating), and the possibility to adapt demand to information from the network or aggregator companies (for example, charging electric cars at night when electricity demand is lower). These systems are expected to cut down energy consumption even with a rise in standby energy or to allow demand-side management by the electricity system operator. While they may decrease or shift energy use, they have impacts in other dimensions such as material depletion (Pohl et al., 2021). Electronics are hardly recyclable and use an increasing variety of scarce materials (Ayres and Talens Peiró, 2013; Graedel et al., 2011; International Energy Agency (IEA), 2021). Moreover, these technologies are not necessarily inclusive due to the cost for lower income households (Tirado Herrero et al., 2018) and due to the complexity of their control (Hargreaves et al., 2018).

4.4. Dwellings

Homes are places full of symbolism and meaning. Despite this strong cultural dimension, dwellings are a very material reality. Dwellings as a technical object are in fact the most common framework in sustainability analysis of the residential sector. In many cases, this even only includes heating, ventilation, and air conditioning (HVAC). The housing stock is made of physical realizations of structural types, where large shares of the total final energy in society are transformed into end uses providing services. Therefore, the analysis must be centered not only on the amount of energy carriers but on the services that they are providing.

Following the central idea presented in section 4.2, there must be a match between families and dwellings. This connects what could be considered “purely technical” with the inherent social side of housing. However, only considering the technical side there are important conflicting criteria for diverse dimensions (e.g., smart home systems may decrease operational energy carrier consumption by increasing material use) (Allwood et al., 2011; Hertwich et al., 2019). Therefore, strategies to tackle a specific point might be shifting important impacts outside the picture if we do not address the issue in a holistic way. The incomparability of the diverse dimensions adds to the large uncertainty in the future: discount rates, climate, availability of new technologies, future patterns of use, population, distribution in household units, etc.

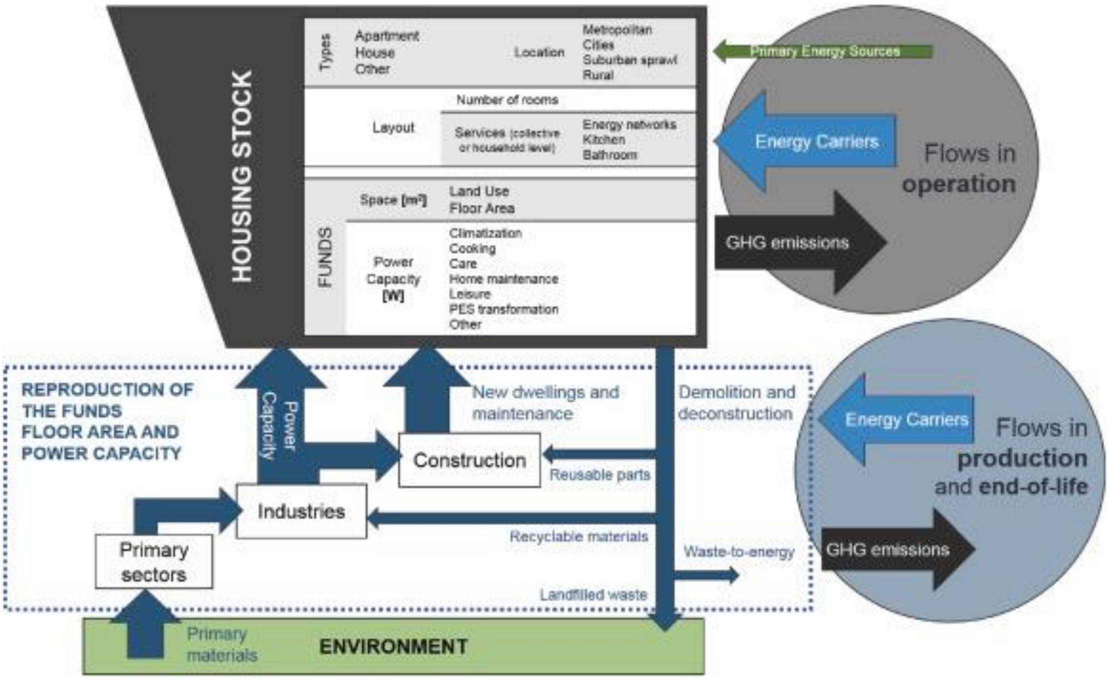


Figure 26 Housing stock characterization and reproduction of funds floor area and power capacity. Flows in operation, and production and end-of-life.

This section starts with the current state of the housing stock, its characteristics, its path dependence, and lock-in. Afterwards, we focus on the sufficiency framework, analysing the economies of scale and levels of service that affect energy use. These measures might have a larger impact than technical changes. We also explore the trade-off between production and operational GHG emissions and energy. Then, we address the growth of the fund floor area, its material requirements, and impacts. Finally, we analyse the role of the construction and real estate sectors.

4.4.1. The state of dwellings

The existent housing sets the initial conditions. It consists basically of houses and apartments, but there are other types such as residential housing for students or the elderly, prisons, etc. Within the set of dwellings, there may be parts that are not used for long-term residential uses, such as holiday homes or tourist accommodation.

A great amount of built environment exists already. While some has been refurbished and will last long in the future, other is of poor quality and expected to be short-lived. The renovation of the stock of buildings is slow due to the long lifespans and cultural values. This locks in practices and uses (Seto et al., 2016) and consequently might generate different kinds of obsolescence: poor construction or design, weak market position, or location (Thomsen and Van Der Flier, 2011). Changes in specifications and requirements for new buildings will take decades to have a deep effect on the performance of the whole system.

In Figure 27 and Figure 28, there are the demographic structures of the housing stock in Sweden and Spain divided into houses and apartments. The decade where most of the Swedish dwellings were built was the 60s. This is a consequence of the million homes program (*Miljonprogrammet*), which was made by the Swedish Parliament in 1965. Following the oil crisis of the 70s and the referendum to replace nuclear power, a Building norm was introduced in 1980, SBN 1980, which tightened the rules for insulation of buildings (Energimyndigheten, 2017). Of the existent buildings today in Sweden, most were built before this building norm. Therefore, the different regulations and building codes are reflected in their contemporary cohorts and qualitative changes in the whole stock take decades to take place.

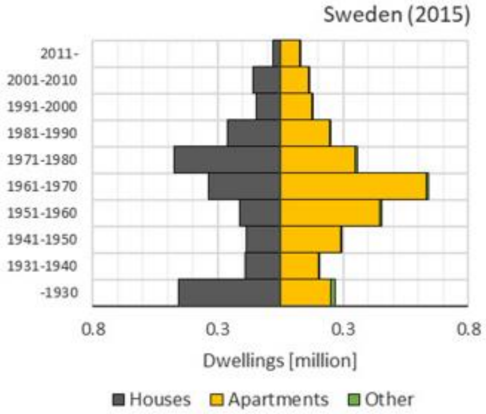


Figure 27 Demographic structure of housing in Sweden (2015) (Statistics Sweden, 2020d)

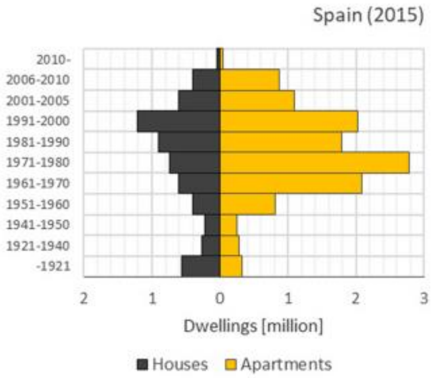


Figure 28 Demographic structure of housing in Spain (2015) (INE, 2015)

In Spain, the largest cohort existent today was built in the 70s, where the average family was of almost 4 members (González de Molina et al., 2019), but the customs in space were lower. To some extent, the construction in a given year matches current or expected types of household units. The only possible low-cost flexibility in the current building stock leans towards individualization (more space per person in a dwelling) instead of towards larger household units, which would require larger refurbishments or the acceptance of downward changes in space per capita.

4.4.2. Economies of scale and level of service

Knowing the characteristics of the dwelling and the power capacity, we could make assumptions on energy throughput and direct emissions in use (operational). A specific performance rate for a building or a device can lead to a large variety of end uses per capita depending on the social configuration around it. Both the household size (economies of scale) and the different types of families, their incomes, and practices affect energy use and emissions. We could even say that a fridge used by 4 people is 4 times as efficient as one used by a single person. These and other issues touched upon in the introduction make essential a framework widening from efficiency to sufficiency, aiming to decrease total consumption in absolute terms by assessing the needs (Darby and Fawcett, 2018; Spengler, 2016; Thomas et al., 2019). This means not only considering the energy quantity or a specific relative improvement but also characterizing the functions and qualitative aspects (space, temperature, shareability, cleanliness, etc.) associated with energy uses.

For that matter, the social dynamics explained in section *4.3* regarding time pressure and its nexus to energy must be understood. The amount and type of appliances and dwellings will depend on social organization (types of household units and size) and the existence of systems of shareability of devices at the community level, which affect time use and daily patterns, on the shift of activities to paid work, which requires the viability of wages, on the ability of states to levy taxes and develop welfare state and the desirability of society to support them, and other changes in daily patterns regarding the expectations on quantitative and qualitative aspects of the activities (e.g., choice, leisure types, space, room temperature and cleanliness).

Structural domestic services are subject to economies of scale in terms both of Power Capacity and Floor Area. Any dwelling customarily has at least a bathroom and a kitchen, with its subsequent equipment, irrespective of size and number of occupants, and these coevolve with legal, infrastructural and cultural conventions (Yates, 2018). If a dwelling is occupied by one or more people, it will affect mainly their size and the size of the devices, only at substantially larger occupations, the number of bathrooms and appliances will increase. Shareability of devices within or between households (washing machine, laundry room or laundromat, fridge, TV, or those used less often such as tools) also reduces the number of appliances that must be manufactured. The case of the washing machine is paradigmatic. In some countries such as Sweden, it already represents an appliance that is commonly shared between households of the same apartment building, requiring organization and rules. Klint and Peters (2021) estimate that the GHG emission savings of a shared laundry room can be 26% in comparison to having washing machines in every apartment. Collective power capacity can be of better quality or performance due to shared costs. This is also true for district heating systems, which operate at a larger scale and increase efficiency compared to individual devices but require a certain level of density of demand.

Some household devices are even used very seldom, i.e., they have small utilization factors (e.g., printers, tools, or specific cooking devices). Consequently, their largest impact lies in their embodied energy and materials, within the manufacturing and material extraction sectors. Ownerless consumption of these items could exist in the form of collective ownership or rental, increasing the utilization factor and reducing the embodied impacts per unit of service. However, the widespread penetration of devices (Cabeza et al., 2018) and thus immediate availability allows patterns of daily routines that require less planning. Ownership in many cases represents a tool of social distinction and symbolic power (Bourdieu, 1984; Mont, 2004; Veblen, 1912).

Moreover, the energy, GHG emissions, and time use can also be divided if tasks are shared so more than one person enjoys its outcomes (cooking, washing clothes, etc.). This means that fewer resources per capita are required for the same function when, for example, cooking for 1 or for 3 people (Hagbert, 2020). Therefore, we can work with fewer devices and/or space (and their embedded resources) (strategy 1.4), or even with fewer devices and time in use if tasks are shared (strategy 1.3). However, this affects current lifestyles, expectations of choices and autonomy, or typologies of families and communities, explained in section 4.3. This depends thus on desirability.

Another key aspect of operational energy use is to understand the level of service that is expected and to understand what the end use or need to fulfill is. Here, we are going to use the example of heating to illustrate it.

The difference between calculated theoretical energy and GHG emissions from an expected level of service and the actual monitored one defines a performance gap (van den Brom et al., 2018). For example, in a sample of 410 homes in the UK, Palmer (2020) found a large discrepancy between the real measurements and their energy performance certificate. The societal availability of cheaper energy services when technical improvements are put in place might ultimately increase overall energy consumption due to the Jevons' paradox (Giampietro and Mayumi, 2018; Polimeni et al., 2008). This difference between expected and effective energy use can be also in terms of lower energy consumption, then called the prebound effect (Sunikka-Blank and Galvin, 2012). The expected energy performance of a building will not be fulfilled if users cannot afford the price, which is common for heating in poorly insulated buildings.

Indoor temperature is a key parameter for calculating heating and cooling loads and thus HVAC energy consumption, one of the largest end-uses in many countries. People expect to live in comfortable environments no matter the external climate. This has generated a convergence of inner temperatures among countries and seasons (Shove, 2004). Even though the maintenance of an adequate temperature is normally framed as a technical problem that must be approached with technology and innovation, it is heavily affected by the conventions on comfort, which are not universal. ‘Adequate’ has a different meaning for different people. Temperature comfort is socially and technically constructed (Prins, 1992) and has changed over time (Chappells and Shove, 2005). Technical systems are designed according to pre-established and not contested conventions of average temperature defined in building codes, for example, those listed in Guillén-Lambea et al. (2017). The questioning of these conventions on temperature is another example of strategy 1.5: decrease quantitative or qualitative expectations of activities (Table 2).

The changes in expectations would enable temperature changes that potentially provide significant savings. Mata et al. (2013) have modelled a set of measures for the housing sector in Sweden. According to this paper, decreasing the indoor air temperature to 20°C provides the greatest energy savings. The rest of the measures require physical changes with energy and material investments in buildings, and only give marginal returns in part because the thermal technical specifications of Swedish building sector are already high. Guillén-Lambea et al. (2017) modelled the energy consumption for heating and cooling of conventional and nZEB buildings in diverse cities in Spain and found significant differences in energy demand even within a small range of room temperatures (for example, savings from 13 to 23% for conventional dwellings when decreasing heating temperature from 20 °C to 19 °C). Sahakian et al. (2021) organized a living lab "heating challenge" in 8 European countries where the participants ended up acknowledging that an inferior temperature than usual could be considered enough. That said, the whole paradigm of space heating for temperature comfort can be challenged as well. Further alternatives to heating spaces can also be a solution, for example, clothing and personal heating devices (Rawal et al., 2020). Verhaart et al. (2015) reviewed literature on personalized comfort systems and their combination with common HVAC systems have an energy-saving potential of up to 34% and an increase in occupant satisfaction.

4.4.3. Energy retrofits and the trade-off of production and operational energy

For the improvement of the energy and emissions performance of the residential sector, we must always consider the social innovation strategies and preanalytical framework explained before related to shareability and economies of scale, and the conceptualization of services. However, the technical improvement of dwellings and power capacity and the substitution of devices with updated technology also play important roles.

The construction of new dwellings or production of power capacity is in part related to the substitution of old appliances to phase-out of certain energy carriers (e.g., electrification of kitchen appliances) (strategy 2.6) or improvements in energy efficiency or lowering emissions (strategy 2.4). In this case, there are trade-offs affecting the two main variables (energy/GHG emissions and materials) and phases (manufacturing in diverse sectors/operational in the residential sector/end-of-life), which at the same time involve different actors (companies, public services, and households). There are two different types of resource uses which are allocated in different societal sectors and depicted in Figure 26: (i) the flows metabolized by the funds – i.e., operational resource uses (residential end uses); and (ii) the flows needed to produce and maintain the funds – i.e., production of power capacity and construction and maintenance of floor area (in the construction and upstream sectors). For example, energy efficiency strategies such as buying a fridge with new technology might shift impacts to manufacturing and upstream sectors in terms of both materials and energy. In practical terms, the end-user, the household, might be perceiving a lower energy consumption, but in overall terms, this might not be true if we consider the embodied resources in production of both the new and the substituted fridge. The construction and manufacturing of new updated products may not always pay back the potential future savings if the substituted product is still new. If the substitution is required at a higher rate for phasing out of energy carriers due to scarcity, the overall energy and GHG emissions balance might be challenging to evaluate. Also, models exploring payback times or building service times involve making assumptions of very uncertain variables such as future uses and innovation in technological upgrades.

In terms of thermal performance, buildings with conventional energy standards generate most of the GHG emissions in their use phase (Anderson et al., 2015). Although Nearly Zero Emission Buildings (nZEB) or other low-energy building standards decrease energy in use for thermal end-uses, there is a larger initial investment (Mirabella et al., 2018; Röck et al., 2020). Vilches et al. (2017) indicate that the share of operational energy in the life cycle of a building is decreasing from 80 to 60%. The timing of the transition becomes important due to the large peak of emissions and other resource uses in construction. Also, the reduction in technical energy carrier consumption clashes frequently with the material efficiency and circularity, for example, with smart homes and the concomitant deployment of hard-to-recycle electronics.

The thermal performance of a building is defined at different levels and is more or less changeable depending on the layer of the building. Some of the characteristics of the outer layers are considered to be especially relevant: orientation, shape, and building aspect ratio (Pacheco et al., 2012), which are set in the design phase and therefore not changeable with a retrofit. This includes the distinction between houses and apartments (strategy 2.8), where houses tend to have larger operational energy and GHG emissions due to heating. This shows that the renovation wave can have a limited effect and that existing building stock has a lock-in in terms of both function and performance.

Coming back to the thermal performance, the level of insulation is calculated with the transmittance (U values) of walls, floor, and roof. In the Swedish case, the U values of windows are equal no matter the age of the building (Boverket, 2010), because the change requires minor work, whereas changing the insulation of the walls and roof represents a deeper retrofit. However, in comparison to other EU countries, overall Swedish U values are relatively low (Entranze project, 2013). Deep refurbishment with an upgrade in thermal characteristics is still not put into practice at the pace that would be expected. While 12.3% of the residential buildings in the EU28 were renovated in 2012–2016, only 0.2% of the residential buildings in EU28 were deeply renovated in energy terms (more than 60% energy savings), 0.1% in the case of Sweden and 0.3% for Spain (Esser et al., 2019).

4.4.4. Expansion of the fund floor area

Housing is currently expanding, with still low rates of demolition in relation to construction. The expansion of the fund Floor Area, provided that monetary dynamics are favorable, is driven by population growth, expectations of space per capita and functions, the increase of one-person households, change of preferred location or type of dwelling ((peri-)urbanization/ruralization) and the demand for other uses (e.g., second homes and tourist accommodation). This expansion is a key driver of materials, energy, and land use. It also determines the functioning of the construction sector and its supplier industries and locks in the demand for resources in the subsequent use of buildings. Therefore, it requires a deep analysis of the existing stock and future needs. This will be large in developing countries such as China, with intense urbanization and expansion of the floor area (Velasco-Fernández et al., 2020b).

The construction of new dwellings generates impacts, but most of them are induced in upstream sectors related to material production (Alcántara and Padilla, 2021, 2020; Frischknecht et al., 2020; Huang et al., 2018). The production of construction materials represents about 11% of the global energy and GHG emissions, and more than half are related to steel and cement manufacturing (Röck et al., 2020). The bulk of materials for buildings in weight corresponds to those most consumed overall: concrete, steel, other non-metallic minerals, and timber. However, there is increasing diversity and amounts of rarer materials, both in power capacity and parts of the building (e.g., insulation).

If it is considered that new buildings are required, some strategies could decrease the impact of materials and construction. These must be a central criterion in the design phase and are difficult or impossible to implement in later stages in the life cycle of buildings. These include: (i) reduction of floor area or downsizing, (ii) lightweighting, (iii) new or improved production technologies of primary materials, (iv) substitution of materials, (v) recycling of materials, (vi) reuse of parts, (vii) increase durability and (vii) increase flexibility.

Reduction of Floor Area or downsizing

Reducing the available space (strategy 2.7) reduces the quantity of materials (embodied resources) and also thermal operational energy. However, it must come with a reflection on what is sufficient space. This can be related also to larger household sizes and economies of scale explained in Sections *4.1.3 Shareability and economies of scale*, *4.4.2. Economies of scale and level of service*. Zhong et al. (2021) define space reduction as the most powerful measure to reduce emissions in material production for buildings. It is also relevant for thermal energy uses, for example as shown by Cordroch et al. (2021) in a model for the German housing heating demand. Pauliuk et al. (2013b) define increasing household size by 15% and decreasing floor area per capita as the combined measures that can cut down GHG emissions by 53% in the Norwegian dwelling stock by 2050. Very high thermal performance standards could be backfired by the increase in the size of dwellings (Gao et al., 2019; Rokseth and Manum, 2021; Stephan and Crawford, 2016; Wilson and Boehland, 2005). Therefore, assessments of energy efficiency using only intensive variables such as energy per area may be misleading (Rokseth and Manum, 2021). Moreover, larger floor area per capita and lower energy per area are usually related to higher incomes (von Platten et al., 2020).

While the fund Floor Area is growing due to both population and household increase, also floor area per capita is increasing. Space standards have evolved through history concomitantly to the expectations of privacy and the number of rooms required by families (Moura et al., 2015; Park, 2017; Roberts-Hughes, 2011). Moreover, new realities may require duplicate spaces, like in the cases of joint custody of children, and telework. A larger dwelling also defines more work to maintain it clean and working.

While there is a trend of downsizing due to the decreasing household size and the shortage of land in cities, data indicate that dwellings are getting relatively larger per person overall (Ellsworth-Krebs, 2020). This is due to the fact that, for example, two apartments for one person are generally larger than one apartment for 2 people. The average housing standards in Europe define minimal aggregate living space (living and dining rooms, and kitchen) of 21,9 m^2 for 2 inhabitants and 19.6 m^2 for 1 inhabitant (Yunitsyna, 2014). Moreover, downsizing, as performed nowadays, is not framed within sufficiency but driven by rising land prices in cities. This reduction is not compatible with prevailing perceptions of sufficient space (Cohen, 2020; Sandberg, 2018).

Lightweighting

Another approach is to reduce the quantity of materials and their embodied impacts: lightweighting (strategy 2.10). Nowadays, the construction paradigm is that of building rationalization, which uses standardized beams with a limited number of cross-section sizes (Moynihan and Allwood, 2014). This entails the use of oversized beams and defensive design strategies used by engineers and required by codes (Dunant et al., 2018). Therefore, they use more material than would be required in order to ensure stability and load-bearing. If the objective of minimizing overall cost would shift to that of optimizing loads at all points, steel and other material use could be minimized at expenses of higher costs and complexity in design. Alternatively, lightweighting could be done by changing materials with a higher strength ratio per weight, for example, composites. However, the initial savings in material quantities entails a future difficulty to recycle them.

Changing production processes of primary materials

Emissions from primary material production of steel and cement are process emissions challenging to decarbonize (Habert et al., 2020; Rootzén and Johnsson, 2017). The production processes of these materials could be transformed (strategy 2.13).The transformation of production chains involves a large number of strategies depending on the material that we are not going to detail here but are available in the literature (Habert et al., 2020; Rissman et al., 2020; Vogl et al., 2018). These include direct reduction with hydrogen instead of coke for steel or increasing use of cement clinker substitutes and include carbon capture and storage systems for cement production. The transformation of the supply chains of primary steel and cement depends on large investments that are made in long investment cycles (Vogl et al., 2021) and are out of the direct control of the construction sector.

Material substitution

Another way to avoid the emissions of primary material production is to find substitutes to those materials. Here, biobased materials play a special role (strategy 2.14). Timber is gaining traction as a carbon-capturing and low material intensity alternative to the emission-intensive materials concrete and steel (Churkina et al., 2020). Increasing wood use in construction is the most impacting material efficiency strategy for reducing GHG emissions considered in the global model of Pauliuk et al. (2021).

However, timber has worse thermal performance than concrete due to its lower heat capacity (less thermal mass and more overheating) (Heeren et al., 2015; Ramage et al., 2017). It must be also protected from humidity and plagues and parts must be sized for adequate fire resistance (Churkina et al., 2020; Ramage et al., 2017).

Sawnwood and wood-based panels come from renewable resources, but their availability is determined by the maintenance of the fund land use (quality of the soil, use of fertilizers, irrigation, etc.), forestry harvest, the increasing competition of other uses (materials, energy, and chemicals) and the conservation of natural areas for biodiversity. In the model of Churkina et al. (2020), only the lower timber content (10 and 50% timber) building scenarios could be satisfied with current harvest rates plus re-directing a part of other end uses such as fuelwood. However, not all forestry products can be used for construction.

In Sweden, wood is used largely for frames in detached houses (around 80–90% (Antikainen et al., 2017), very large compared with other countries such as Germany: 2% (Mahapatra et al., 2012)) but still minor in multi-dwellings (around 8.8% in 2014 (TMF 2016)). This shows that it is already conventional practice in some countries for some building types. However, in many cases bio-based are still to be introduced in regulations to make possible its generalized use in structures other than low-rise buildings.

Recycling

Existent buildings and their parts are hardly reusable or recyclable. Most of the construction waste is currently deposited in landfills, or downcycled (e.g., backfilling). This cascading of materials from the rest of the economy can also increase the secondary inputs to construction. Currently, old scrap is mostly recycled into construction steel, which has lower specifications in comparison to other steels (Pauliuk et al., 2013a). We will face a challenge in the future management of the end-of-life of current building stock, which has been mostly built in the last decades without consideration of reusability or recyclability and it could become obsolete simultaneously. The recycling of materials (strategy 2.12) could still be possible to a certain extent, but it would require dismantling buildings carefully separating the different materials instead of demolishing and disposing of them (more labor and planning). Logistics, cost, lack of regulation, and time are considered the main barriers to recycling (Ghaffar et al., 2020). On the one hand, the large amounts of materials that are in a building facilitate their recycling (potential higher collection rate), but, on the other hand, the fact that they were constructed with wet joints and composite materials difficult to detach (e.g., reinforced concrete) hinders it.

The production process of secondary materials can be 10% or 50% of the primary production for aluminium and steel (Gutowski et al., 2013), respectively. In some cases, the incentive to recycle does not come from the reduction in resources in secondary material production since it might not be as beneficial considering sorting, collection and transport, but from the scarcity of raw materials (Schmidt, 2021). The overview of the system puts into question circularity. The building stock is expanding and therefore accumulating more materials. Therefore, the system requires continuous inputs of raw materials. Buildings designed now for recyclability will take decades to be actually recycled. Demolition does not play a sufficiently large role in providing secondary materials yet. And even in a steady-state context, there are always a limited maximum recycled content potential, losses due to dissipation and low concentration, and the inclusion of tramp elements limit recyclability (Graedel et al., 2011; Pauliuk et al., 2013a; Schmidt, 2021; UNEP, 2013; Verhagen et al., 2021).

Design for disassembly

Another strategy is to implement design for disassembly in new construction (strategy 2.11). This way, the structure and envelope of a building are not a monolithic unit with a clear lifetime anymore. Instead, the life cycle of components is expected to be longer than the buildings in which they take part. Parts are kept within the anthroposphere and must be useful in the future for further uses in new buildings.

The new projects with modular buildings with reusable parts would affect a very small share of the current housing stock. Now, these reusable parts are in fact newly manufactured, but a system (regulations, market, etc.) must be created to manage their future reuse. The design objective is not to calculate an optimum with standardized new parts anymore, but adapting the design to the available parts from deconstructed buildings or standardized parts (Fivet and Brütting, 2020). This potentially extends the life of parts but decreases material efficiency and limits lightweighting at the level of the building (Addis, 2006; Gorgolewski, 2019). Also, not all types of materials and parts can be reused at the same level (Iacovidou and Purnell, 2016).

Reusable parts require more work, special transport, storage space, and infrastructure to maintain and guarantee their functionality (Hillebrandt et al., 2019), while business as usual depletes the available materials by simply throwing them away into landfills (Giampietro, 2019). This represents a whole new paradigm that requires new logistics, design methods and tests to ensure the mechanical performance and geometric tolerances of reused materials (Durmisevic, 2006; Fivet and Brütting, 2020; Tingley and Davison, 2011). This includes creating reverse logistics and reused component markets, defining disassembly plans in the design phase, and more specific technical aspects such as using dry or reversible mechanical instead of wet connections. On the other hand, it has other potential advantages: industrialization of processes, standardization, and prefabrication of parts. This multidimensionality is shown in Küpfer et al. (2021), which proposes a multi-criteria decision framework for diverse levels of reuse of structures and dimensions: environment, risk, costs, and construction complexity.

Both recycling and disassembly require more working time than demolition, challenging the financial viability of deconstruction and reuse. The current low cost by volume or mass of primary construction materials in comparison to wages hinders their reuse or recycling. Transport distances also play a key role in the economic and environmental profit and if very long could even overtake avoided impacts of primary materials and components (Chong and Hermreck, 2011; Ghisellini et al., 2018).

Durability and flexibility

Buildings could be designed to be long-lasting. Studies point out that making sturdier and long-lasting products pays off when the initial investment is large (Skelton and

Allwood, 2013; van Nes and Cramer, 2006) (strategy 2.5). This also requires good maintenance during the lifetime.

Durability is not only a matter of sturdy structures but also of an adaptable function and/or form (strategy 2.9). In fact, in many cases, the demolition of a building is not due to the degradation of the structure or components, but due to functional or locational obsolescence. The lack of flexibility does not only affect the materials and their future uses in new buildings, but also the possibility of adapting the use of existing buildings by changing their layouts (Schneider and Till, 2005). For example, the evolutionary change in size and number of rooms could accommodate a family throughout its different phases over time. In this sense, there is the paradigm of flexible buildings (De Paris and Lopes, 2018; Femenias and Geromel, 2020; Schneider and Till, 2005; Till and Schneider, 2005) (strategy 2.9), which could rely on indeterminate spaces (soft vs hard use (Till and Schneider, 2005): multi-functional rooms) or the modularity and changing partitioning of buildings (soft vs hard technologies (Till and Schneider, 2005): e.g., flexible wall divisions, switchable rooms joinable with adjacent apartments, folding components).

Indeterminate spaces use to be linked to a provision of more space (Till and Schneider, 2005), thus potentially backfiring in the short term the resource use improvements in the long run. The invested resources might be useful for a longer time but are larger in the first place. In any case, flexibility must be projected as a core objective from the design phase, which implies a cost that developers may not be willing to take (Tarpio et al., 2021). The structure and services (e.g., wiring, and electrical outlets) and types of construction, which are not currently flexible, may lock the possibilities of rearranging floor plans. Therefore, most existent buildings cannot accommodate large changes over time. This flexibility of function and form is expected to be required in a society in permanent change and innovation but might not be as much in a steady-state economy.

4.4.5. Construction and real estate sectors

The functions of the construction sector are refurbishment, maintenance, demolition, and new construction not only of housing but also of other types of buildings and infrastructure. In other words, it adapts the fund Land Use for different functions and multiplies it into Floor Area.

Moreover, it is a key economic sector. The construction sector represented directly in 2015 6% of the gross value added and 7% of the working time in paid work for both Sweden and Spain (Eurostat, 2019a, 2019b). The sector needs a continued expansion of the stock or an important investment in refurbishment. It is not only the sector devoted to building houses to fulfil societal demands, but it requires a continuous demand for housing to maintain production and therefore the existence of the sector. In Spain, during the years previous to the housing bubble burst in 2008, the vertically integrated construction employment represented 19.7% in 2004 of the Spanish economy (Bielsa and Duarte, 2011), with 12% directly devoted to the construction sector.

For the sake of the immediate revenue of construction activities, the additions to the built environment are designed according to current or near-future expected most profitable demand instead of having a strategic long-term perspective. Therefore, the existent housing stock is a stockpiling of dwellings designed according to needs at the time of construction as perceived by developers within the limits of regulation. The future needs of the users, the municipality or the country are not necessarily included if governments do not enforce them.

In consequence, homes are not only the place where people live but also an economic asset. We cannot conclude the paper without mentioning this aspect, which is crucial because people spend a significant share of their income to access housing by means of rent or mortgage. Rents represented 11% in Sweden and 3% in Spain of the monthly expenses in 2015 (Bouzarovski et al., 2018). In Spain, ownership of housing is more common than in Sweden, and it represents 8% of the value added (L68A – imputed rents of owner-occupied dwellings). This is important when assessing the capability of households to access a dwelling and the further large investments in maintenance and refurbishment. The lower income population tends to live in buildings with worse thermal performance and landlord-led retrofits might entail processes of renoviction (García-Lamarca and Kaika, 2016).

The economic character of dwellings is most clear in the real estate sector, its financial manager. In the case of the EU28, it represented in 2015 11% of the value added (including L68A – imputed rents of owner-occupied dwellings) and 1.1% of the HA in paid work (Eurostat, 2019a, 2019b). In this context, dwellings are not only the places where people live but also an economic asset. This has led to financialization and housing bubbles (Andreucci et al., 2017; García-Lamarca and Kaika, 2016; Jorda et al., 2014; Naredo, 2019, 2009). The ratio of household mortgage debt to GDP in 2009 was 64% in Spain and 82% in Sweden (García-Lamarca and Kaika, 2016). The material dynamics are more tightly driven by financial cycles rather than by the needs of the population.

Several dynamics and trade-offs described in the paper are influenced by access and other property rights over dwellings. For example, distributing dwellings not through the current logic based on private property (purchasing capacity and inheritance rights), but to other socioeconomic characteristics (e.g., distance to work and social network, household size, age, etc.) would help improve the relations between people and buildings and sustainability. Also, the property or access format affects the form. Property or access types enable or limit the flexibility in distribution of space and rooms between adjacent apartments. In a similar way, the provisioning of services generates technical requirements. For example, the payment of electricity defines the way meters and wiring are installed. The institutions involved in dwelling ownership or access and the provisioning of services also affect the possibility of investments (e.g., retrofits) and the policies that governments can implement.

4.5. Conclusions

Interdisciplinarity is key for sustainability. Technical solutions are insufficient and should be adequately contextualized. We must really understand social dynamics and their entanglements with technology to propose coherent and transformative practices. In this paper, we have provided an overview of factors for the sustainability of the residential sector and assessed qualitatively trade-offs and impacts in energy, materials, time use, and social organization of possible measures ranging from social innovation to construction methods. To this effect, we have framed biophysical flows and funds using MuSIASEM, as well as around current cultural and institutional settings using practice theory. Some important variables are left out of the analysis, such as health, water, and contamination.

The residential sector is the center of daily life. Homes have changed throughout history, both in functions and form. Household units of organized individuals live in diverse typologies of dwellings (houses, apartments, and others, with different layouts) and these configurations have shaped the diverse dwelling cohorts. A clear definition of the functional boundaries of the residential sector is not possible, even more since activities at home are intimately related or even partially substituted by those in paid work.

Strategies such as downsizing and shareability are often used in models without considering their social consequences: the coherence with practices. People organize in diverse types of household units now mainly based on the nuclear family and increasingly in the individualization of life. The steady fall in household size has increased the number of dwellings in use while the shareability of space, materials, and devices is decreasing. Alternatives based on sharing and collectivization generate economies of scale but pose a desirability challenge. Some of the social innovation strategies that could be put in place require deep changes in the way we frame households, institutions regulating access to dwellings, and also in the organization of communities and companies. Time use is a key variable for sustainability not sufficiently acknowledged in the literature, with an important nexus to energy use and appliance ownership.

The built environment consists of large already invested materials, emissions, and energy. The merely technical side of dwellings has many trade-offs. The concepts of durability, material and energy efficiency (in operation and production), monetary cost, recyclability, flexibility, and modularity can be mutually exclusive. The emerging combination of long-lasting housing and other infrastructure in types of urbanism and municipalities generates strong lock-in in their uses and related dynamics such as mobility. Therefore, new construction concepts may only tackle new buildings, which take decades to take over the whole system due to the large life of buildings. Moreover, it requires a new culture of work for architects, engineers, town planners, and other construction workers. Finally, we must consider that many of these technical strategies may entail higher up-front costs that might not be acceptable for developers, which do not have a high interest in the future uses of buildings. The longevity of buildings sets a challenge for future uses and potential lock-in of functions and resource use, and also in regard to the accountability for maintenance and end-of-life.

The current centrality of the narrow definition of energy efficiency does not provide a framework robust enough to improve the residential sector. Sustainability oriented to artifacts and individual behavior should be shifted towards functions and systems. This would make it possible to contextualize local efforts, generate truly innovative processes and provisioning of services and evaluate trade-offs across scales and dimensions. In this paper, we have reviewed and discussed a set of actions to improve the sustainability of the residential sector. Beyond this review, we have proposed an interdisciplinary framework to analyze the sustainability of the residential sector as the integration of families/households units and dwellings, identifying key entanglements between them, with paid work sectors, and with the environment. We expect this work to help in the holistic interdisciplinary understanding of household metabolism that will ultimately set the foundation for transformative changes and policy for social, economic, and environmental sustainability.

Families/household units

	Action	Examples	Possible effects and trade-offs: Energy and GHG emissions — Operational	Production	Floor area, power capacity and materials	Human activity	Social organisation and desirability
Shareability and economies of scale	(1.1) Increase household size/larger occupation	Families living together for longer, young people not emancipating to individual units but to shared flats, transforming household units to larger multi-family units with common spaces and activities	Decrease (shared activities: shared energy use). If people live together but still do not commit to common activities (e.g., cooking), the operational use might not decrease significantly	Decrease due to shared spaces (kitchen, bathroom), infrastructure and devices	Fewer dwellings, larger but relatively smaller (basic services like kitchen and bathroom and many other devices are shared so less space per capita is needed). Compatibility with current dwelling stock must be checked: number of rooms, size, etc.	Less overall time use if activities are shared (cooking, household maintenance, etc.) but larger synchronisation and coordination	Requirement of organisation and commitment (less individualism and loneliness, but potentially more conflicts). Purchasing power within the market enables individualisation and choice power. Acceptance of new family types and/or living in a community.
	(1.2) Shifting activities from the household to the community or market	Cooking in community kitchens or restaurants, organised childcare	Less energy per unit of service (economies of scale)	Decrease (few devices are needed)	Fewer devices but larger ones are required. Less space is required at home, but more collective space is required (but with economies of scale). This kind of space might lack in existent buildings.	Increase time in collective activities and requirement to give salaries if they are considered paid work. Potential economies of scale and quality increase by specialisation of work	Requirement of organization and commitment in communities, or significant changes in companies from product to service provision. Risk of depersonalization. Cultural change on how needs are fulfilled. Requirement of density of demand for providing the service at scale, related tc the type of municipality and urban forn
	(1.3) Sharing the use/service of power capacity	Carpooling, cooking for the whole household unit	Less energy in use per unit of service	Decrease (fewer devices are needed)	Fewer devices are needed	The time of the device use is shared but it requires strong time-space synchronisation with others	A strong requirement of organization (less flexibility and more commitment t schedules).
	(1.4) Share power capacity	Carsharing, common laundry rooms in apartment buildings, tool libraries	Possibility to have better or more diversity of devices (due to shared cost) and to update their characteristics more often (due to its more intensive use and thus shorter lifetime)	Decrease, but devices may be used less carefully.	Fewer devices are required. Less space is required at home but alternative common spaces to store those devices must be found	Not immediate access to devices. Sometimes devices are needed at the same time so its utilisation factor cannot increase (e.g., special or larger cooking devices for Christmas or car use for commuting).	Requirement of organization (less flexibility) and commitment to care for common devices. The social distinction given by the ownership of devices might disappear with sharing.
Allocation of time	(1.5) Decrease quantity or qualitative expectations of activities	Lower indoor temperature in winter and higher in summer, not washing clothes every time they are used, simpler food, living closer to work	Decrease		Fewer devices might be needed	Decreasing time pressure	Acceptance of lower standards or new daily routines (e.g., suits in offices in summer are not compatible with warm weather)
	(1.6) Give flexibility to the household time budget	Members of the household without strong scheduling and with time to devote to household needs (e.g., childcare, elderly care): stay-at-home parents, part-time workers, retired. Flexible paid work.	Flexibility in the time use budget makes the use of technology (and energy) less necessary due to the decrease in time pressure. It could be useful to adapt to demand response.		Fewer devices might be needed (e.g., car for matching multiple activities with strong scheduling such as paid work and childcare)	The time use of the household improves. The possibility that some members do not have access to own (sufficient) income and therefore have an economic dependency on others	If household units are larger, retired members could provide support to othe members. If household units keep the nuclear family model, the model would be a stay-at-home parent. Alternatives for increasing flexibility could be found from paid work or public or private services.

Table 2 Actions to increase sustainability of the residential sector at the household unit dimension (social innovation) and effects on diverse variables

Dwellings			Possible effects and trade-offs				
	Action/strategy	Examples	Energy and GHG emissions		Floor area, power capacity and materials	Human activity	Social organization an desirability
			Operational	Production			
Amount of power capacity and its control	(2.1) Use less power capacity	Bike instead of a car, manual chopping instead of a blender.	Decrease.	Decrease.	Less materials and devices. Potential increase in sharing devices if they are used only seldom.	More time is required for the same activity ('Time investments in the environment')	Social structures should allow for flexibility and changing expectation activities.
	(2.2) "Smart homes" and digitalization	Sensors, internet of things, automatization.	Higher stand-by baseline electricity use. Use of appliances can be shifted given external information on energy prices (allowing demand response)	Increase.	Increase need of electronics, internet infrastructure, devices difficult to recycle with increasingly diverse materials.	Automation allows services to delink from presence of inhabitants (more flexibility in time use). More possibility for multitasking, more stress.	Comfort might increase with automatization (e.g., turning on heating before inhabitants get hom but might be expensive, difficult to accept or learn to use by certain pa of society. Use to be associated wit symbolical power, which increase i desirability.
Maintenance and renovation (trade-off of operational and manufacturing resource use)	(2.3) Improve thermal characteristics	Refurbishment of households increasing insulation, construction of nZEB buildings.	With better insulation, buildings need less energy to provide same service. Expectations and thus service might increase at a lower cost (Jevons' paradox). Some characteristics for thermal performance are set in early design stage that are not changeable during refurbishment (e.g. orientation), so the improvement via refurbishment is limited.	Increase. The distribution of emissions and energy use changes: a larger peak of impacts in construction phase and lower operational in time	More materials.	Maintaining jobs in construction sector.	Business as usual of practices. Buildings with worse energy performance are usually related to lower income households. The high costs of refurbishment can be a burden to them or generate proces of renoviction.
	(2.4) Substitution for decreasing operational energy use	Replacement of heating systems or appliances with a better energy certificate.	Less energy in use but must be checked with energy in manufacturing (shorter lifetime would increase overall energy consumption) Possible rebound: a fridge that spends less energy by unit of food but that is larger and therefore ends up using more energy.	Increase. The balance between lifetime and improvement in operational energy must be considered.	Larger amount and rarer materials difficult to recycle (e.g., more electronics, sensors)	Maintaining jobs in manufacturing, less jobs in reparation.	Business as usual in daily life.
	(2.5) Extend life of devices - ensure durability	Repair, refurbishment, remanufacture, maintain, not buying up-to-date devices when old ones still work.	More energy in use (not updated technology and wear)	Less energy in manufacturing in the long term	Less materials required in the long term. Possibly more materials are needed for the same product for sturdiness. Materials stay in use longer (fewer recycling loops). Devices must be designed for repair and maintainability.	Less jobs in manufacturing but more in repair.	Acceptance higher risk of failure of devices. Design for durability and repairabili
	(2.6) Substitution for change of energy carriers	Electrification of cooking and heating, biomass for heating, electric vehicles (in order to decrease operational GHG emissions or avoid stock depletion of fossil fuels).	The important factor is the change of energy carriers, which can affect the supply systems and their quality (specially its storage), and not so much the quantity of energy carriers (which are not comparable).	If the transition of power capacity follows current renovation rates, it may be the same. If the transition replaces devices that could last more time, it increases.	In the energy sector:competition of renewable energy with agriculture (biofuels, PV panels).	Moving to 100% renewables could imply important demand flexibility, which would alter the allocation of human time.	Acceptability of the replacement of devices if new ones are considered expensive or old ones are in good condition.

Table 3 Actions to increase sustainability of the residential sector at the dwellings dimension (technical) and effects on diverse variables

Design/layout (dwellings)	(2.7) Space reduction/ Downsizing	Smaller rooms, smaller dwellings, kitchenless homes.	Less energy for heating.	Decrease.	Less materials in construction. If downsizing is related to adapting to smaller household size, this could overall increase the number of dwellings, area, and number of appliances. Activities increasingly shifted to dwellings may require extra space (telework, etc.).	Less time for household maintenance (e.g., cleaning).	Acceptance of living in smaller spac Definition of what sufficient space i Sharing spaces with more people (larger household size) for econom of scale.
	(2.8) Give preference to apartments (vs houses)	Urban planning that concentrates new dwellings in apartments in the city instead of promoting houses in the suburban sprawl.	Better heating performance in multistorey buildings. Less relative capturing area for solar energy generation in relation to consumption. Urban form more favorable to public transport and proximity of services (less energy in mobility).	Decrease.	Reduction in land use. In turn, density of demand of services allows some collective services and more compact infrastructure (e.g., district heating, public transport, waste collection). Depends also on the existent housing.	Density of population given by apartments allows proximity of services (less time for mobility, economies of scale).	There are shared spaces that requi organization. There is less privacy a private green areas.
	(2.9) Flexible housing	Indeterminate spaces for diverse possible uses (avoiding scripting).	-	Decrease, since there is less functional obsolescence, and the space is used more effectively in the long run.	Flexible indeterminate spaces might also be related to larger spaces. In this case, the material benefits are in the smaller obsolescence and longer use, and not in the sense of using less floor area		
		Flexible floor plans with modular rooms or walls, foldable furniture, etc.	Potentially less energy for heating since spaces are more effectively used.	Decrease, since space can be adapted to the use.	The floor area can be adapted to the household size and thus can avoid overkill. However, this space must be well coordinated with the surrounding spaces (matching with the needs of all affected apartments). Flexible wall divisions might not have good acoustic quality.	Less time for cleaning and maintenance.	The dwelling can adapt to the diffe configurations of family along time alternative household units or to different uses. However, institutior and regulations should be able to manage the changes of layout (contracts, ownership, etc.).
Materials	(2.10) Light-weighting	Choose carefully structural elements not with a the minimum number of sections, but adapted to the specific use, increasing the variety of types of components.	Check impact in thermal load and thus thermal performance.	Decrease due to less energy for material production.	Less raw material is used. Structural design with smaller safety factor.	More time in engineering design (high salaries) and also in construction (more carefully managed).	Adapt work processes. Business as usual in daily life of use
	(2.11) Reuse of parts	Demountable parts, modular structures.	-	Less energy for material production.	Less raw materials are required in the long run. Quality control to ensure mechanical properties. Material use is less optimized: designs must be adapted to existent materials and might use more material than required if optimized for lightweighting. In global terms, Housing stocks are growing (so more materials are required in new construction than the ones demolished). Old buildings that are currently being demolished were not designed for reuse.	Less work in construction in situ (prefabricated components). More work in deconstruction and selective deconstruction. Salaries are higher than current material cost (which could change with higher environmental protections and increasing raw material scarcity).	Requires new paradigm of design fc disassembly: reverse logistics, desig risk assessment, etc. In general, professionals do not have experien in designing reusable buildings and manage deconstruction. Logistics a more complex (space for storing lai amounts of materials, transport of large parts). Business as usual in daily life of use

Dwellings

			Possible effects and trade-offs				
	Action/strategy	Examples	Energy and GHG emissions		Floor area, power capacity and materials	Human activity	Social organization an desirability
			Operational	Production			
Materials	(2.12) Recycling of construction material	Recycled aggregate concrete, secondary steel.	-	Less energy for material production, but maybe it is required to recycling. Energy for transport if it travels long distances.	Housing stocks are increasing (so more materials are required in new construction than the one demolished). Most buildings that are demolished were not designed for recycling. Material can mostly be downcycled or cascaded. Use of secondary materials requires also raw material and, in many cases, does not fulfill original characteristics. Recyclability is limited by tramp elements and a sufficient concentration of scrap. The cost of recycled materials is higher than raw materials.	More work in deconstruction and classification of materials.	Maintenance of construction secto activity (but with higher costs). Business as usual in daily life of use
	(2.13) Change production processes of primary materials	Steel production by hydrogen, carbon capture in cement production.	-	Change of energy carriers, important changes in the production infrastructure.	Creation of new infrastructure for new processes.	-	These changes do not depend on th construction sector itself. They mus be carried out by material compani that may be even foreign, whose infrastructure is very large, have la investment periods.
	(2.14) Use of alternative biobased materials	Timber as a substitute for steel and concrete.	Worse thermal performance.	Carbon sequestration depending on the end-of-life and management of the harvested land.	Limited yearly supply of renewable material with increasing competition of other end uses (energy, chemicals, etc.). Not all wood outputs are useful for building. Potential for reusable modular construction.	Reduction of building time (modular prefabricated parts).	Concrete's and steel's largest end-u is construction and decreasing dem would decrease activity and jobs in those sectors. Building codes might still not be adapted to biobased materials. Professionals and companies do no have enough expertise.

5. The international division of labour and embodied working time in trade for the US, the EU and China

The content of this chapter was published in Ecological Economics. Based on Pérez-Sánchez et al. (2021)*. Minor changes have been introduced to the main text.*

5.1. Introduction

Biophysical limits have been an essential concept in the sustainability debates starting with Malthus (1798), the Limits to Growth (Meadows et al., 1972), and more recently the planetary boundaries (Rockström et al., 2009). Whereas external environmental limits have been thoroughly analyzed, internal societal limits have gone unnoticed. Human time is a crucial internal societal limit. Just as individuals have a 24 h budget of time a day to fulfill needs and duties, societies have a given budget of human time to sustain their metabolic activities. Social culture, institutions and technical structures at the upper level define the possible patterns of time use of individuals, what we call the social practice (Shove et al., 2012). Human time can be categorized in: physiological overhead, leisure, education, unpaid domestic work carried out by families (especially by women), and paid work (Giampietro et al., 2012). The latter is the main variable of study in this paper.

Paid work is an essential input to the economic sectors in market economies. The availability of paid work time depends broadly on demographic variables, i.e., the number of inhabitants and the relative size of the economically active population. Each society defines aspirations and regulations of who in this demographic structure is allowed or expected to participate in paid work, e.g., retirement and minimum working age, working women, and expectations on educational attainment. At another level, the total working hours per worker per year are determined by work regulations, namely holidays, working hours a day, safety conditions for different jobs, and parental leaves. Apart from changing this social organization, countries have followed two other strategies to adjust the profile of labor allocation in the economy given the budget of working time, which are those analyzed in this paper: increasing exosomatic energy use to boost labor productivity and outsourcing of activities.

Energy is a fundamental factor in the functioning of complex systems and shapes societal organization (Smil, 2008). The industrial revolution supposed a historical tipping point in the re-shaping of the economic structure of modern societies, associated with a fossil-fuel based metabolic regime. However, it was only during the 1950s that the use of cheap fossil fuels and other resources started to skyrocket. That Great Acceleration (Steffen et al., 2007) allowed a larger substitution of labor by mechanisation that led to increasing societal complexity (Hall and Klitgaard, 2012; Tainter, 1988; White, 1943).

Now we are able to get much more and a more diverse output relative to working time. At the same time, it has generated social acceleration and, paradoxically, time-pressure in the lives of individuals (Reisch, 2001; Rosa, 2013). More products and services are produced per hour of labor, but many more goods and services are required both in production and consumption.

Technical innovations such as international shipping and IT have shaped the modern world-system (Castells, 2010; George, 2013). Globalization has led to increasing geospatial separation of production and consumption, and, as a consequence, to an unprecedented displacement of impacts through international trade. Indeed, the fragmentation of production chains and specialization across countries obscure national and regional sustainability assessments, and hence compliance with the UN Sustainable Development Goals (SDGs) and the Paris Agreement.

This problematic flags the need to build consumption-based indicators (Liu, 2015; Tukker et al., 2020). The literature on this topic with case studies on environmental variables is large and growing. Regarding the regions of study in this paper, there are diverse examples such as the environmental and resource footprints of the European Union (Tukker et al., 2016), carbon dioxide emissions embodied in foreign trade in China (Zhao et al., 2014), virtual water in trade in China (Chen et al., 2018), and a more recent one on the flow of embodied carbon in China, the EU and the United States (He and Hertwich, 2019).

Nevertheless, sustainability does not only require the feasibility in relation to ecosphere constraints, but also the viability of the socio-technical organization and the desirability for its members (Giampietro et al., 2009; Saltelli and Giampietro, 2017). Just as with environmental impacts, outsourcing allows an increase in the consumption of working time without its local economic and social costs (reducing human time for care, education, retirement, etc.). Even though most of the consumption-based studies analyze environmental impacts and resource intensity, there is an increasing interest in this social perspective (Arto et al., 2014b; Hubacek et al., 2016; Steinberger et al., 2012; Wiedmann and Lenzen, 2018). In the specific topic of paid work, there are studies on the British textile industry in the late 18th and early 19th centuries (Hornborg, 2006), labor and wage footprints (Alsamawi et al., 2014), labor footprints in the EU (Simas et al., 2015), “bad labor” footprints (Simas et al., 2014), and the study of diverse embodied variables in trade including labor in 2015 (Dorninger et al., 2021).

While these studies have pinpointed the extent of outsourcing of such environmental and social impacts through pressure indicators, it is often overlooked that the externalization of energy and labor-intensive activities underlies the socio-economic organization of society. To assess that, we analyzed both the internal working structures and trade relationship with an aggregated manageable number of sectors and countries. Studies that include all countries usually end up focusing on those with the most exceptional patterns. We instead choose deliberately the US, the EU, and China, which are the largest importers and exporters worldwide in terms of the value of trade (Eurostat, 2018). These regions play a major role in the world system in other diverse dimensions. Moreover, their political and economic influence has sparked conflict in the last years precisely due to trade (Emmott and Barkin, 2018; Paletta and Swanson, 2017; Tankersley and Bradsher, 2018).

In this paper, we assess the labor embodied in production and trade between China, the EU27, the US and the rest of the world in 2011, within the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) framework (Giampietro et al., 2013, 2012) at the level of both regions and economic sub-sectors. Moreover, we relate time with secondary energy use in order to better understand the nexus of social and environmental constraints. We provide new insights into the effects of trade on their metabolic patterns embedded in the worldwide economy. We explore human time as a societal limit, its role in production and consumption, and the dependencies that arise from trade. In this way, we can study how externalization of specific economic sectors allows some countries to concentrate its budget of paid work to higher-value services and other services that increase the wellbeing of their population. This paper complements the analysis of the metabolic patterns of China and the EU in Velasco-Fernández et al. (Velasco-Fernández et al., 2020b).

5.2. Materials and methods

5.2.1. Human activity as a global limit

Analyzed in a given year, the total global amount of funds is by definition constant. In the case of human activity, it is measured in hours and calculated multiplying the population by 365 days a year and 24 h a day. This amount of human time must generate closure for all activities carried out in the society in that year. The use of funds, if maintained properly, does not exclude their future use. In contrast, stocks (mineral or fossil fuel reserves) are defined by its depletion as they are exploited, and their current use excludes use for future generations. This means that there is a clear zero-sum game in the considered timeframe in terms of embodied funds (human time) in traded goods and services, where some countries can expand their existing funds at the expenses of others.

In individual economies, we can find large differences in the size and characteristics of the funds used for producing or consuming traded commodities, in the flow/fund variables and other qualitative characteristics, which are key drivers of unequal exchange: labor productivity, wages, workers' rights and conditions, etc. The limitations of the budget of time can also be avoided by increasing the productivity of funds, using more energy and other resources. Considering more variables and sectors (energy, materials, infrastructure, etc.), the definition of the patterns of human activity is further defined by the mutual information and impredicativity of the whole system in what is called the Sudoku effect (Giampietro and Bukkens, 2015).

This means that a complex combination of structures, requirements, decisions and trends defines (and at the same time is defined by) the amount of funds used for each function (e.g., number of workers in agriculture, area devoted to crops) and left unmanaged (e.g., wild forests). Changes in the profile of human activity depend thus on several factors: demographic structure, cultural characteristics determining the current social practices, infrastructure requirements of time for its functioning, economic structure, and power within the global market. By adopting an articulated representation of the metabolic pattern of countries, it is possible to study the implications of the characteristics of human time allocation across different levels of analysis (individuals, households, countries, the world economy). As we have already said, we are focusing on working time in the market economy, linking the country with the global level. This is only a part of the whole set of relations that exist in the metabolic pattern of social-ecological systems, that we will consider but not fully analyze.

5.2.2. Variables of analysis

- Human Activity (HA, in h per year), fund: working time spent in market activities. Labor time is considered a fund in the yearly timeframe, although it also fluctuates at larger timeframes due to demographic, economic, and social changes. Only paid work in the market economy is accounted for in this paper for all variables. Despite the indispensability of unpaid domestic work for social reproduction (Carrasco Bengoa, 1988; Hoskyns and Rai, 2007), systematic data for all countries is still lacking and wage labor statistics are still central. There could be as well indirect inputs (not accounted here) in the form of activities of social reproduction in the exporting societies. Further work would include a thorough analysis of the use of time in all sectors of society.
- Economic Job Productivity (EJP, in $/h), flow-fund ratio: Value added generated per hour of work.
- Energy Metabolic Rate (EMR, in MJ/h), flow-fund ratio divided in electricity and thermal energy.

It is important to note that in order to study the factors determining the profile of allocation of human time associated with the profile of energy uses we have to focus on the relation between hours of work, the characteristics of power capacity, and the tasks to be achieved in the working activity. Within the metabolic pattern, we can divide energy transformations in two categories: (1) those referring to the catabolic phase – in which favorable gradients found in the environment (the primary energy sources whose existence does not depend on human agency) are destroyed in the energy system in order to generate secondary energy useful for the final uses of energy in society; and (2) those referring to the anabolic phase – in which secondary inputs are used by combining labor and technology to build structural elements and to express functional tasks.

In our analysis of the use of the human time we are focusing only on the anabolic part. In order to analyze the time required by a worker using a tool powered by electricity, it does not matter whether the input of electricity has been produced by a coal or by a hydroelectric plant. Therefore, the Energy Metabolic Rate that describes qualitatively the given activity must be calculated in relation to the use of secondary energy. For this reason, we consider only the consumption of secondary energy flows outside the energy sector, namely the energy carriers consumed in the various paid work activities. That is, in this paper we do not aim to calculate the energy footprint of consumption, but how human activity is a key limiting factor in the reproduction of socio-ecological systems. This entails identifying the economic transformations depending on the availability of paid work that regulates the use of secondary energy in the economy. Therefore, this study does not include the quantities of primary energy that are taking place in the energy sector, the catabolic part, for example the coal spent in producing electricity. It also neglects the concomitant effects on GHG emissions or the depletion of fossil fuel stocks. Assessments of these quantities are certainly relevant for studying other aspects of sustainability and can be calculated using a different accounting scheme to answer a different research question. As a matter of fact, MuSIASEM has been already used for some of these different types of analysis, including exosomatic energy systems (Di Felice et al., 2019; Diaz-Maurin and Giampietro, 2013; Parra et al., 2020; Ripa et al., 2021), and endosomatic energy systems: (Cadillo-Benalcazar et al., 2020; Renner et al., 2020a).

5.2.3. Data and calculations

The Trade in Value Added database (TiVA, DVA_{ikj}) was the main source of data (OECD, 2019)[1]. It is a set of indicators based on the inter-country input-output OECD tables. It reveals how the value of final demand goods and services consumed within a country is an accumulation of value generated by many industries in many countries in global production networks: *Value added embodied in final demand*. Value Added data captures better than Trade the role of countries, avoiding the double counting implicit in gross flows of trade (Koopman et al., 2014). Countries do not produce from cradle to gate, they are contributors to intertwined global processes where materials and intermediate products cross borders multiple times before getting to their final consumers (Sturgeon, 2001). Clear examples of this international distribution of production are the global value chains of electronic products (De Backer and Miroudot, 2013) and Barbie dolls (Tempest, 1996). Moreover, some products do not even undergo any physical transformation in countries which only are intermediate ports due to lower tariffs or to avoid sanctions, namely re-export or entrepot trade.

Countries play different economic, political, and productive roles in global production networks. Even though the final analysis included two supra-national regions of analysis (the EU and Rest of the World) and an aggregated classification of sectors, the results were calculated with the most disaggregated values available by industries (34) and countries/regions (45). This classification could have influenced the results, such as the inclusion in the same category of Wholesale and retail trade. The classification of economic activities hides differences in activities which belong to the same category but have completely different resource uses, and even the same activity can be performed differently. For example, for Pulp and Paper, Finland has a very energy-intensive industry devoted to pulp, whereas Portugal has a less capitalized pulp sector, and in Italy, the activity of the sector is oriented to final paper products manufacturing (Velasco-Fernández et al., 2019). The classification of economic sectors was finally further aggregated in 8 categories for the analysis in the figures (reference table in the Appendix): Agriculture, Mining, Industry, Utilities, Construction, Transport and telecom, Services, and Finance and offices. The regions of analysis are China, the United States,

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[1] It was after the publication of this article that I got familiar with Input-Output tables. Using Exiobase for both the Leontief matrix and the extensions for the multipliers would have been a better option, avoiding the problem of coherence of sectoral classifications.

and the European Union (the 27 Member States in 2011) and are complemented by the Rest of the World.

The data of Human Activity by country and industry (HA_{ik}) was taken from the Exiobase version 3.3 database (Stadler et al., 2018; Tukker et al., 2013a; Wood et al., 2015) summing the categories of Employment hours by skill and sex in the factor inputs table.

Energy Throughput (referring to secondary energy or energy carriers) by country and industry (ET_{ik}, electricity or thermal) was taken as well from the Exiobase version 3.3 database (Stadler et al., 2018; Tukker et al., 2013a; Wood et al., 2015) and the materials table, more specifically the category Electricity, and the sum of categories Emission Relevant Energy Carrier for thermal. As noted earlier, we included only energy carriers to end uses outside the energy sector, excluding primary energy or carriers used to generate other types of carriers, e.g., natural gas to produce electricity in cogeneration power plants. For this reason, the economic sector Utilities (C40T41 – Electricity, gas, and water supply) is not included in the analysis of Energy Metabolic Rates. We differentiate between thermal and electricity, acknowledging their different natures and paths within the energy system (Giampietro and Sorman, 2012).

To get the embodied time (HA_{ikj}), the Economic Job Productivity of each country-industry (EJP_{ik}) was multiplied to the trade in value added (DVA_{ikj}) generated by the consumption of each region. An important hypothesis laying down the calculation is that each sold monetary unit had the same economical and technical characteristics no matter the country of final demand. Nevertheless, it is known that companies that export have different characteristics than those who produce for domestic consumption, at least in the case of China (Upward et al., 2013).

$$EJP_{ik} = HA_{ik} \cdot \sum_j DVA_{ikj}$$
$$HA_{ikj} = DVA_{ikj} \cdot EJP_{ik}$$

i: country of production.

k: industry of production.

j: region of consumption (China, EU27, US or Rest of the world).

In order to get the Energy Metabolic Rate of each country-industry (EMR_{ik}), we divided Energy throughput (ET_{ik}) by its working time. The consumption-based EJP and EMRs include the value added, labor, and energy carriers in domestic production that is consumed locally (not exported) and those embodied in imports.

$$EMR_{ik} = ET_{ik} \cdot HA_{ik}$$

5.3. Results and discussion

5.3.1. The regions in the global picture

In Figure 29, we can see the relative share of the regions of study regarding different variables in a production-based perspective: total population, human activity, value added, electricity and thermal energy in paid work. Even though the sum of the US, the EU, and China represented only 31% of the population and paid work time, they generated more than half of the value added and consumed about half of the electricity, and thermal energy of the world in paid work. What is more, the US' and the EU's shares are more disproportionate. Together, they generated 45% of the value added worldwide and accounted for 32% of electricity and 27% of thermal energy consumption in paid work, despite their relatively small total population size (4% and 7% respectively) and human activity invested in paid work (4% and 6% resp.).

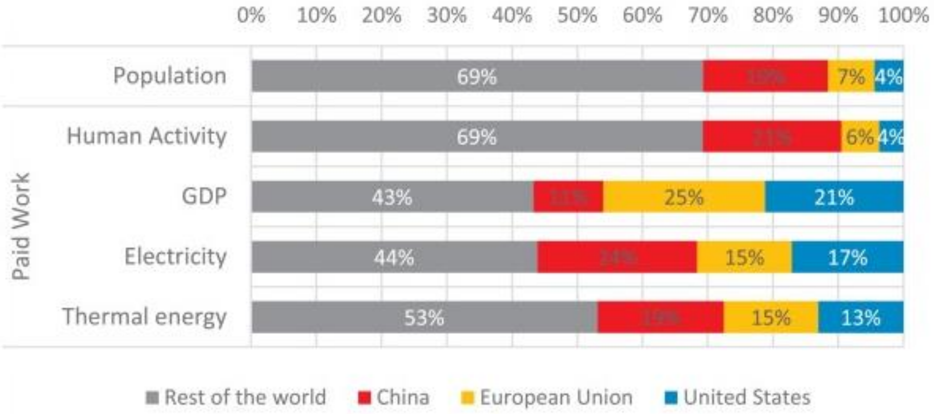

Figure 29 Relative share at world level of inhabitants, value added (VA), and human activity (working time in h) and energy (electricity, and thermal energy) invested in paid work for China, the EU, the US and the rest of the world (ROW) in 2011.

Rest of the World (ROW) was the largest region in terms of inhabitants and working time and includes a large number of countries very diverse in their economic development. Because of this heterogeneity, its average values of consumption carry little meaning. The EU and US comprised 70% of the population in “more developed regions” in 2010 according to the UN (United Nations Department of Economic and Social Affairs. Population Division, 2019). This category includes all countries in Europe and Northern America, plus Australia, New Zealand, and Japan. Therefore, that 30% left in ROW may follow a pattern similar to that of the US and EU. The exporting net situation of ROW shown in the results is very likely to be exacerbated in less developed regions.

International division of labor

Figure 30 shows the local work structure of the regions of analysis and the global picture. Each country participates differently in the international division of labour. Most working time was still on Agriculture, forestry, and fishing both for Rest of the World (33%) and China (44%), whereas it represented only a small share in the EU (6%) and the US (2%). However, working time itself is not a good proxy of production, and even more in agriculture, where very diverse production types coexist worldwide, characterized by their Energy Metabolic Rate (energy per hour of labour). Most of these workers in China are low-tech peasants, whereas animal farming and the use of machinery for crop production define agriculture in the EU and the US. The large agricultural production of the US is vital for its food security but at the same time minor in value-added terms. It requires solely a tiny amount of workforce (about 2%) but it is boosted by power capacity and other inputs, for example, energy, pesticides, fertilizers, and water.

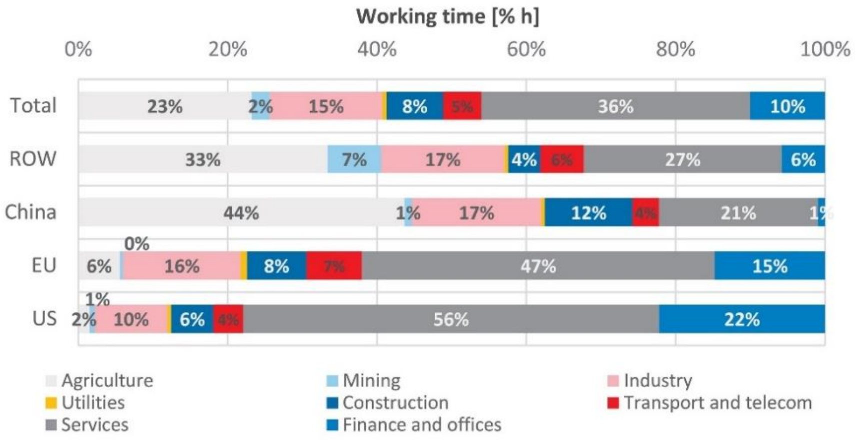

Figure 30 Shares of working time (%h) per sector for all regions and the world in 2011

Transport and Finance and offices manage material and monetary flows worldwide. Transport and logistics are essential structures to organize in time and space the increasingly complex global production networks. The US (22%) and the EU (15%) had especially large shares in Finance and offices compared to the other regions and the global level (10%).

Some activities are very connected to geographical locations. Soil and climate determine agriculture, whereas Mining is even more limited to the specific locations of profitable ore stocks (plus social acceptance and less strict environmental regulation). In another way, most of the subsectors in Services are linked to the place where users live, such as education, healthcare, retail, or government. Thereby, these latter activities are not outsourceable. This is the category where most people worked at a global level (36%) but represented even about half of the working time in the EU and the US.

5.3.2. Production, consumption, and trade

Regions

Figure 31 shows the total working time in production and trade for each region of analysis. Positive values and bars in darker colors refer to Consumption of the country (imports and a part of the domestic production), and negative numbers to Exports (the part of exported domestic production). The colors of the bars define the country of production in the case of the positive values, and the country receiving exports in negative: grey for the rest of the world, red for China, yellow for the EU, and blue for the US.

Here we can see that both the US and the EU were net importers of working time and rely more on work performed outside of their boundaries. 50% and 54% respectively of their consumption was satisfied with embodied work in imports. More specifically, 10,5% and 6,8% of the embodied work in their consumption was Chinese. In contrast, China showed larger self-sufficiency. 91% of its consumption was local and the EU's and the US' imports contributed marginally (0,4%). It even had an almost balanced trade with the Rest of the world. We can relate these results to those in (Alsamawi et al., 2014), where they classify countries as masters and servants. Masters import cheaper labor from servants. Both the US and the EU are masters, whereas China is an intermediary country, neither master nor servant. Similarly, the world-system theory of Wallerstein (2011) classifies the US and the EU as core regions and China as semiperipheral.

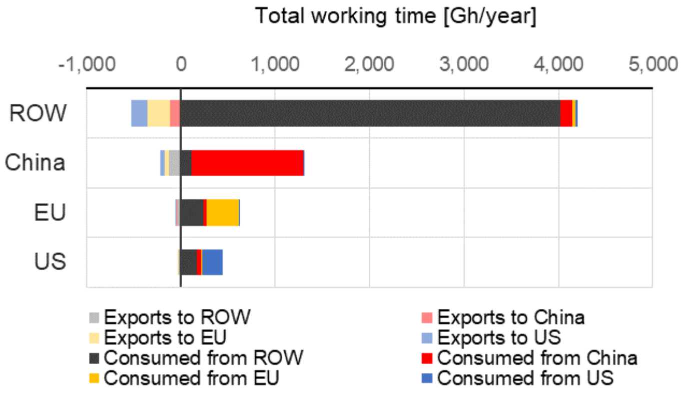

Figure 31 Total working time (Gh/year) in exports, production, and imports by region in 2011.

Human activity in exports ranged from 10% to 15% of the local production for all regions of study. What it is a large input of time per capita for the EU and the US is a relatively low export for the rest of the world. This means that it is relevant that core countries such as the EU and the US have smaller populations than that of the importing peripheral region, both China and most of the rest of the world. However, the rest of the world comprises a heterogeneous variety of countries. Some of them are developed countries likely to have the same net importing characteristics as the US and EU, whereas less developed countries would export a larger share of the work embodied in their local production. Existent literature suggests as well this situation (Alsamawi et al., 2014; Simas et al., 2015, 2014). A further, more detailed analysis would be needed to discern differences in the countries in the rest of the world.

With the values per capita, we can analyze the consumption of citizens, i.e., the number of hours that are required to sustain the consumption of an average citizen in each of the regions, shown in Figure 32. In this perspective, we can see the US and EU had larger embodied working time in consumption than China. Moreover, China was the largest exporter per capita, and it exported more than it imported. Local working time per capita in the same China was larger than those of the US and the EU. However, imports made that the larger consumer of working time was the US' average citizen, with 1430 h/(cap·yr), which was about twice the paid work invested in the local economy: 783 h/(cap·yr). Afterward, there was the EU average citizen with 1238 h/(cap·yr) (760 locally invested) and the Chinese with 963 h/(cap·yr) (1033 locally invested). Compared with China and the Rest of the World, the EU and the US relied more on embodied working time both in relative (per capita) and absolute terms (total hours), despite its smaller population. These results add to the literature on environmental impacts and material consumption-based indicators: what means a better life for the EU and the US is a cost for others (Brand and Wissen, 2018).

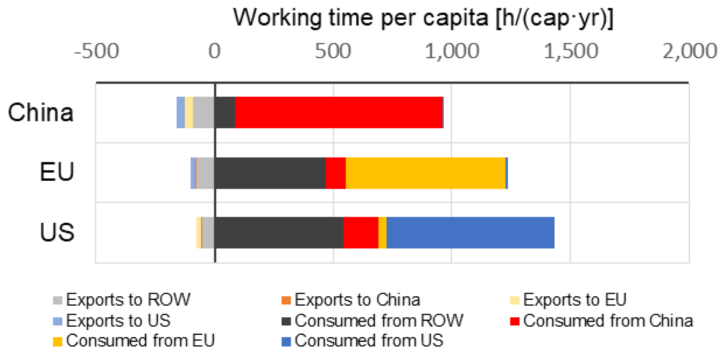

Figure 32 Working time per capita (h/(cap·yr)) in exports, production, and imports by region in 2011.

Economic sectors

Besides the differences in population, the economic sectors also play different roles. Figure 33 shows the embodied labor time per capita for each economic sub-sector and region. At first sight, there was large self-sufficiency in the sectors Utilities and Construction. Construction requirement of labor per capita was way higher for China, which shows the state of urbanization and building of infrastructure.

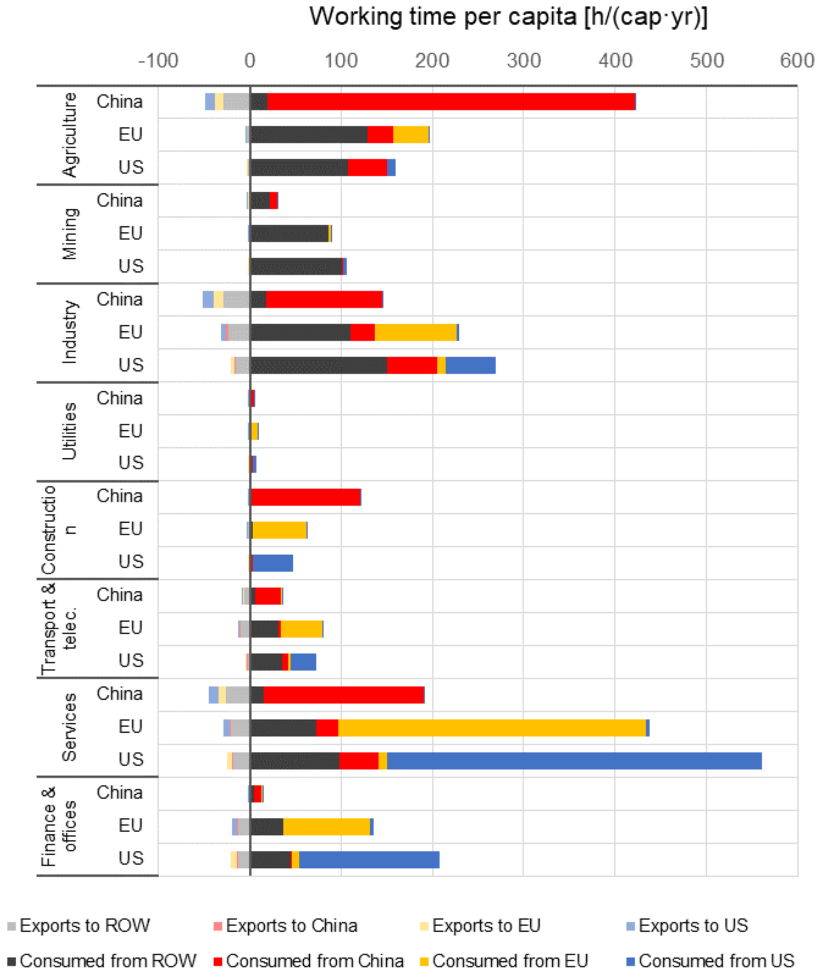

Figure 33 Working time per capita (HA, in h/(cap·yr)) in exports, production and imports by region and sector in 2011.

In all the other categories, the Rest of the world had significant participation, which becomes especially relevant in Mining. The almost complete externalization of Mining and quarrying in the EU might be a consequence of resource scarcity, Not In My Backyard (NIMBY) opposition to mining projects, and the existence of the global commodities market. Working time is not a direct proxy of the production since a lower number of working hours can be compensated by a larger use of energy and machinery, here identified by high Energy Metabolic Rates (EMR, see appendix). In the case of the EU and the US, EMR for Mining are the largest or second-largest both for electricity and thermal energy. The associated large Economic Job Productivities (see appendix) of these sectors might explain their generation of significant environmental impacts.

In general, both the US and the EU relied strongly on work performed outside its borders in material extraction and transformation (Agriculture and fishing, Industry, and especially Mining and quarrying). For these categories, embodied time in imports represented 75% (EU) and 87% (US) of consumption, whereas for China it was only 10% (Figure 33).

With respect to Industry, although imports of embodied time from China to the EU and the US were significant (12% and 20%), the Rest of the world was their largest supplier (48% and 56%). China showed larger self-sufficiency and larger exports per capita. China is thus believed to be the factory of the world. Nevertheless, in many cases, it imports intermediate products, and it is only the final assembler of goods: a part of the Global Production Networks. *Made–in-China* products have many other manufacturing locations where vital intermediate processes are performed.

The difference in Energy Metabolic Rates in industry reflects not only larger mechanisation but also the fact that different subsectors are located in different countries. Industries in the EU and the US had higher production-based EMR and Economic Job Productivities than China. That means they are very technology-based, niche and have limited but international demand, such as pharmaceutical, aerospace, IT, and robotics. This is why a large share of their production is exported. On the other hand, the Chinese government has developed the Made in China 2025 strategic plan, which aims to upgrade technologically the country's manufacturing. Its textile industry is a clear example of a labour-intensive industry that has started to be relocated to third countries like Bangladesh or Sri Lanka. It is no surprise that this transformation of the Chinese industry is giving rise to increasing competition and international tensions (Paletta and Swanson, 2017; Tankersley and Bradsher, 2018).

A paradigmatic example is the relationship between the US' and China's Industries. The average US consumption per capita of embodied time from the local industry and imported from China was approximately the same, about 55 h/(cap·yr). Whereas the Economic Job Productivity of the 55 h/(cap·yr) of Chinese industry was only 10 $/h, the EJP of the US counterpart was 7.5 larger (75 $/h). Of those 55 h imported hours from China, the larger shares were in labor-intensive subsectors with even lower economic productivity. 18 h were in the subsector Computer, Electronic and optical equipment with an EJP of 5.1 $/h, and 9.8 h in Textiles, textile products, leather, and footwear with an EJP of 5.7 $/h.

The US and the EU's workforces were devoted mainly to Services and Finance and offices (78% and 62% of the working time respectively). Despite their smaller overall workforces, they consumed about twice of China's labor per capita in Services. The difference widens in the case of the Finance and office work sector. The EU and the US are service-centered societies and rely on the work performed elsewhere for their material consumption.

The relatively low EMRs in Services and Finance and offices show that what could be defined as a more sustainable society is, in fact, only based on value-intensive services. That thus depends on the overseas manufacture for their material needs, externalizing their environmental impacts and work requirements. Substituting work in the industry, characterized by high EMRs, by work in services, with low EMRs, ends up with a decrease in direct energy consumption that could be understood as energy efficiency improvements with a production-based approach.

Services have become central through a process of de-industrialization of specific industries in the US and EU. This led to environmental quality improvement, but also the loss of local well-paid jobs and increasing unemployment (Smil, 2015). In the global economy, transnational companies take advantage of lower wages and less strict regulations in poorer countries. However, these transnational companies often maintain headquarters in the home country and their subsequently higher value added activities in Finance and offices that support production and consumption (research, design, marketing, logistics, retail), the so-called smile curve (Del Prete and Rungi, 2017). Some scholars point out that the control of service activities only represents an overestimation of the role of developed countries, and the capture by transnational corporations of value generated in production in the developing south (Ali-Yrkkö et al., 2011; Reinert, 2011; Roy, 2017; Smith, 2012).

A consequence is an increase in exports of Finance and offices, which can be seen in the large amounts of labor exported by the EU and the US. However, these exports are fluid and not restricted to specific infrastructure. Therefore, office work is susceptible to be as well relocated to developing countries such as China as their younger generations get higher education (Chang et al., 2013; Smil, 2015).

On the other hand, there are other Services, which in many cases are labor-intensive and define the level of wellbeing of the population. Within this category, there are structural sectors such as wholesale, public administration, and defense, but also many services directly connected to social welfare that are non-outsourceable: education, healthcare, hotels and restaurants, retail, and social work. In this case, both local and consumed working time were greater for the US and the EU than China (local allocation: 411, 332, and 180 h/(cap·yr) respectively).

Some activities can be carried out both within and out of paid work. Even though we would need time use statistics on unpaid work to perform a thorough analysis (Hoskyns and Rai, 2007), we introduce two examples: children's care and cooking. Even though we would need time use statistics on unpaid work to perform a thorough analysis (Hoskyns and Rai, 2007), we introduce two examples: children's care and cooking. Local time per capita in the subsector Health and social work were 98 h/(cap·yr) for the US, and 10 h/(cap·yr) for China, with lower availability of doctors and an approach to dependency care based on unpaid work. Retired Chinese grandmothers take care of children to a great extent while young mothers are working. Women have a low retirement age in China, 50 or 55 years old depending on the type of job. Its planned raise due to the aging population will pose a challenge to this care system (Yu et al., 2018). As another example, a large share of the time in services in China came from Hotels and restaurants (70 h/(cap·yr) compared with 32 in the EU or 50 in the US). This working activity decreases time in domestic work for food acquisition and preparation allowing longer workdays for the other workers.

Finally, some services related to entertainment do not only need large amounts of labor but also the availability of leisure time (Zipf, 1941). Hence, it makes sense that the US and the EU, which have lower working time per worker and a larger share of nonworking population, have more services as well.

5.4. What about an international reallocation of working time?

In this section we propose a scenario of reallocation of working time in the global economy to flag the relevance that this issue should have in sustainability discussions. As we have seen, the societal limits associated with the budget of human time in the US and the EU have been overshoot by means of trade and capitalization. Citizens of these countries enjoy a living standard that would require much more work than what they are allocating in their market economy. This expansion of consumption by core countries has been obtained at the expenses of peripheral and semiperipheral countries, such as China, which are competing to achieve that central role and become working time importers, increasing pressure on the global time budget.

This large net import of embodied work in core countries challenges proposals like working less for sustainability (Antal, 2018; Kallis, 2013). Instead, it makes us rethink developed societies to turn upside down the international division of labor that leads to an unequal exchange (Wallerstein, 2007). This is a political question that needs a broad debate on the interconnected social practices and environmental pressures generated by the relation between core, peripheral and semiperipheral countries in the globalized economy. We pose a question to make a first rough exploration: what if core countries agree on reinternalizing most of the economic activities they are outsourcing at the moment.

Table 4 presents a summary of the hours and number of workers in production and trade, and population for China, the EU, and the US. It includes a rough assessment of how many equivalent workers would be needed to fulfill the current levels of consumption with the existent hours per worker. In 2011, these hours per worker were significantly lower for the US and the EU (1718 and 1759 h/(worker·yr)). The extra virtual workers of the EU and the US would be 110 M and 117 M (against 216 M and 142 M existent workers in 2011), whereas China would gain 42 M virtual workers that are now working for imports. Clearly, this would not be a viable scenario for the EU or the US. 83% of the population of the US in 2011 should work to cover all the work that is consuming. Instead, assuming that workers would accept Chinese working times (2222 h/(worker·yr) – an increase of about 30% of current yearly workload), the EU and the US would require “only” 58 M and 62 M extra workers respectively, which couldn't be tackled with current unemployed people alone. A reinternalization would negatively affect their material standard of living and jeopardize their existent decarbonization plans and goals.

Unpopular societal changes could include later retirement age, less education before entering the workforce, an increase of the workload in paid work, a reduction of the work force in the service sector to increase it in primary and secondary sectors. Within a given societal budget of human time, an enlargement of working time in a category necessarily implies decreasing that of others. For example, increasing the paid work will reduce unpaid work or leisure work, and thereby will heavily affect the current pattern of social practices.

Table 4 Summary table of hours, population, workers and required equivalent local workers to fulfil consumption for China, the EU and the US.

Population data from (United Nations. Department of Economic and Social Affairs. Population Division, 2019). Percentages of workers are in relation to the total population in 2011.

	Working hours per year					Number of people [10^6]					
	Total		Per capita		Hours per worker	Population	Workers				
	[10^9h]		[h/cap]				Production		Equivalent for consumption		Difference
	production	consumpt.	production	consump.	h/worker		Total	%pop	total	%pop	
China	1393	1299	1033	963	2222	1348	627	47%	585	43%	-42
EU	387	619	773	1238	1790	500	216	43%	346	69%	130
US	244	446	783	1430	1718	312	142	46%	259	83%	117

In terms of sectors, the imported jobs for the EU and the US are mainly in primary and secondary sectors that were dismantled via deindustrialization processes. Some existent service jobs may be worthless to society (Graeber, 2019) and easy to eliminate, others could be substituted or complemented by technology. However, a significant decrease of labour-intensive services to people (e.g., education and healthcare) affecting wellbeing levels could be necessary in order to decrease material dependency. An international reallocation of working time is not a mere re-allocation of hours in an excel spreadsheet. Jobs are linked to out-of-work practices, abilities, cultural values, knowledge, infrastructures, and natural resources.

This shift would as well require rebuilding industrial infrastructure. However, the current high level of energy use is generating problems in both stocks (fossil fuels, materials for renewables), and sinks (GHG emissions, pollutants). A transition to a lower energy consumption would force a decrease in the Energy Metabolic Rates of activities. This would require larger amounts of labour to produce the same output, something that would further increase the pressure on the human time budget. We can only conclude that current socio-technical organization should be radically reconsidered, prioritizing those activities that are essential.

Table 5 Distribution of Human Activity, Value Added, Thermal energy and Electricity in the EU for Exports, Consumption from local production and Imports.

										Flow/fund indicators		
		Human activity		Value added		Thermal energy		Electricity		EJP	EMR$_{therm}$	EMR$_{electr}$
		h/cap	%	$/cap	%	MJ/cap	%	MJ/cap	%	$/h	MJ/h	MJ/h
Exports		101	8%	4,494	12%	16,718	14%	3,286	14%	44	165	32
Consumption	EU	672	50%	27,901	76%	70,881	59%	14,279	62%	42	105	21
	Imports	566	42%	4,168	11%	32,758	27%	5,447	24%	7	58	10
Total requirements EU		1339		36563		120356		23012		27	90	17

In Table 5, there is a global assessment of Human activity, value added, thermal energy and electricity for the EU in 2011 in exports, consumption from local production and imports. We could understand exports and consumption as a budget of time that is necessary for the functioning of the EU (we could even go further and calculate the embodied time in the intermediate goods for local production). Exports generate favourable trade balances that allow for acquiring imported goods and services. What we see is that human activity is the variable where imports represent the largest share in this budget (42%), and value added the smallest (11%). The EJP (value added generation per hour of work) for imports is more than 5 times larger in the EU compared to the imports. The EJP and EMR for exports (44 $/h, 165 MJ/h and 32 MJ/h) are larger than the ones for consumption of local production (42 $/h, 105 MJ/h and 21 MJ/h).

5.5. Conclusions

The global budget of human time is a societal limit to consider in the sustainability discussion. Global working time allocation among countries is a zero-sum game. However, regional time budgets can be eased by means of technical capital or avoided altogether by externalizing some of the activities required by society. Core countries have a favourable embodied labour trade balance at the expense of peripheral countries, similar to other well-known variables such as GHG emissions, water, or energy. This additional time consists mostly of cheap labour from material transformation sectors (primary and secondary).

The size of the importing core countries plays a key role. Only a small part of the world population can enjoy a large surplus of embodied working time without generating too large social and political tensions somewhere else. The global budget of work explains the struggle for hegemony by the emergence of developing countries such as China. International trade and globalization have given rise to global production networks, which assign specific functions to each region and build a worldwide division of labour. Countries compete for the higher value-added economic structure that allows a greater consumption, more labour-intensive services to people, and shorter working hours.

In this paper, we calculated the embodied quantities of labour time in production, consumption, and trade for China, EU27, and the US in 2011 and their relation to final energy use and generation of value added. The fund-flow perspective and the

MuSIASEM framework allowed us to analyse the metabolic pattern of the regions, their economic sectors, and the dependencies that arise from trade.

In descending order, the consumption of embodied working time for the average citizen was the US, the EU, and China. What is more, the products and services that the US and the EU consumed required almost half of the working time available to these economies invested out of their boundaries. Trade and intense capitalization allowed them to work fewer hours per worker, to have a smaller fraction of employed population and to concentrate the paid work on high value-added sectors and services to people. Imports for the EU and the US embodied a great number of hours especially in agriculture, mining, and industry. Therefore, their working time surplus is dependent on vital processes happening abroad.

China's economic structure showed a different pattern, and agricultural activities still had the greatest share of workers. In general, China was more self-sufficient but still required imports from mining, an activity related to the geological existence of stocks. Embodied working time in imports from the US and the EU was not substantial.

These differences raise a political question: a rather small part of the world population is relying on labour from the rest of the world. Alongside this, there are also known ecologically unequal exchanges in relation to consumption of materials and generation of environmental impacts. Finally, the dependence of the EU and the US on essential production processes outside their boundaries is posing a risk in a world with growing tension due to the development and competition of emerging countries like China, India, or Brazil. The outsourced economic activities in the EU and the US could not be internalized within their current socio-economic structure and societal expectations of working time. This internalization would increase of energy consumption in material transformation activities, moving them away from their regional sustainability goals.

6. Energy metabolism of the automotive industry in European Union countries – implications of functional specialisation in biophysical performance

The content of this chapter has been submitted for publication.

6.1. Introduction

In some European countries, the auto industry has a great symbolic and political role, triggering public discussion on sustainability transitions. On the other hand, different stakeholders consider jobs and value added as main outcomes, even more than the production of vehicles itself (Di Felice et al., 2021a, 2021b; Pichler et al., 2021). Variables like employment, trade and value added have already been included in analyses of the European automotive industry in the economics and geography literature (Klier and Rubenstein, 2011; Lampón et al., 2016, 2015; Lung, 2004; Sturgeon et al., 2008). However, other fundamental variables for sustainability, such as energy consumption and emissions, have been largely overlooked.

Moreover, a multidimensional analysis is not enough. To understand the biophysical performance of this industry, we must contextualise its metabolic characteristics to the national economy and across its lower-level subsectors. This way, we can examine on the one hand, how the national characteristics might define or relate to the sector of analysis and, on the other hand, the more specific functions that the sector is playing.

This paper aims to describe the metabolic patterns of the European automotive industry in 8 of its main countries in a multi-dimensional and multi-scale way, considering energy carriers (electricity, and thermal), GHG emissions, working time, and gross value added. To do so, we use the end-use matrix, a tool from Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM). This tool has been previously used in industrial sectors for the comparison between manufacturing sectors in Bulgaria, Finland and Spain (Velasco-Fernández et al., 2018), and for the pulp and paper industry in EU countries (Velasco-Fernández et al., 2019). We provide a metabolic perspective from ecological economics, relating it to the literature on economic geography and political economy. Through this richer characterization, we can cluster the countries according their biophysical performance and unravel the emerging functional specialization, and spatial dynamics in the European Union. This approach shows the criticalities of simplistic indicators such as economic energy intensity, that can lead to misleading conclusions of decoupling.

The organization of the paper is the following. First, we will present the approach based on the MuSIASEM and one of its tools, the end-use matrix. Second, we present the results on production and size at the focal level: the motor vehicles industry (MVI).

Third, we describe the size of MVI within the corresponding paid work and manufacturing while comparing their metabolic patterns. Fourth, we analyze value added and working time at the lower level divided into three subsectors to assess the effect of functional diversity more specifically. Finally, we discuss the results and present the implications for sustainability and the conclusions.

6.2. Methodology

MuSIASEM is an accounting framework for analyzing the metabolic pattern of social-ecological systems (Giampietro et al., 2014, 2012, 2009). The end-use matrix is one of its fundamental tools (Velasco-Fernández et al., 2020a, 2018). It allows studying the nexus across scales and levels by characterizing economic sectors in a multi-dimensional way. The End-Use Matrix and its predecessor MuSIASEM multi-scale metabolic analysis have been applied to the study of countries and regions (Andreoni, 2019, 2017; Iorgulescu and Polimeni, 2009; Ramos-Martín, 2001; Ramos-Martín et al., 2009; Serrano-Tovar and Giampietro, 2014; Silva-Macher, 2015; Sorman and Giampietro, 2011; Velasco-Fernández et al., 2020b), cities (Pérez-Sánchez et al., 2019), islands (Ginard-Bosch and Ramos-Martín, 2016; Marcos-Valls et al., 2020), the residential sector (Chen et al., 2021; Toboso-Chavero et al., 2021), and industries (Velasco-Fernández et al., 2019, 2018).

The variables and their data sources are listed in Table 6. These are classified into flows and funds, according to Georgescu-Roegen (Georgescu-Roegen, 1971). Funds define the size of the structural components of the system that must be maintained during the period of analysis. The only fund considered here is Human Activity (in Mh), in other words, the working time in the sector. This data comes from National accounts employment data by industry (Eurostat, 2019a) and Annual detailed enterprise statistics – industry and construction (Eurostat, 2021b); see Appendix for clarifications on the matching at the different levels.

Flows are either inputs that are metabolized or outputs produced by the system. This paper analyzes the following flows: production of vehicles, Gross Value Added, GHG emissions (outputs) and Energy Throughput (inputs). Production of vehicles includes both the four main types of vehicles (passenger cars, Light Commercial Vehicles (LCV), heavy trucks, and buses) and their simple aggregation (i.e., not weighted). This data comes from EAMA (European Automobile Manufacturers Association, 2019). Gross Value Added at the level C29 (Eurostat, 2019b) is in Chain linked volumes 2010-million euro, whereas, for the lowest levels (Eurostat, 2021b), it is in Value Added at factor cost (see Appendix). Direct GHG emissions from Eurostat (2021a) include only direct emissions of the sector from the categories “Greenhouse gases” and “Carbon dioxide from biomass used as a fuel”. Energy Throughput comes from the category “End use” in Energy supply and use by NACE Rev.2 activity (Eurostat, 2021c). We divide it into electricity and thermal, considering the fundamental qualitative differences between these kinds of energy carriers (Giampietro and Sorman, 2012). However, figures also use a Gross Energy Requirement aggregated as thermal equivalent for clarity.

Table 6 Extensive variables of analysis and data sources

	Variable		Unit	Definition	Data sources
FUND	Human Activity	HA	Mh	Paid work time	(Eurostat, 2019a) (Eurostat, 2021b)
FLOWS	Production of vehicles		units	Passenger cars, Light Commercial Vehicles (LCV), Heavy trucks, Buses, and aggregated total.	(European Automobile Manufacturers Association, 2019)
	Value Added	GVA	M€	Gross Value Added – Chain linked volumes 2010-million euro	(Eurostat, 2019b)
		VA		Value Added at factor cost.	(Eurostat, 2021b)
	GHG emissions	GHG	ton CO_{2eq}	CO_{2eq} + CO_{2eq} of biomass used as a fuel	(Eurostat, 2021a)
	Energy Throughput (electricity, thermal, and Gross Energy Requirement)	ET_{el}, ET_{th}, ET_{GER}	TJ	Gross Energy Requirements have been calculated using the partial substitution method assuming a conversion efficiency of 38,6% (International Energy Agency (IEA) and World Bank, 2014) for electricity.	(Eurostat, 2021c)

To compare the metabolic characteristics of countries, we use flow/fund rates, always having the fund Human Activity as a reference. These are:

- Vehicle Production Rate (VPR): vehicles produced per 1000 hours of work.
- Economic Job Productivity (EJP): Value Added produced per hour of work.
- GHG Emission Rate (GHGER): direct greenhouse gases emitted per hour of work.
- Energy Metabolic Rate (EMR_{el}, EMR_{th}, EMR_{GER}): energy carriers consumed per hour of work. This is a proxy of the capitalization/automatization of the industry.

The levels of analysis and their correspondence to the NACE Rev.2 classification are depicted in Figure 34. The central sector (level n) is the division *D29-Manufacture of motor vehicles, trailers and semi-trailers*. This division is the most disaggregated with the largest availability of data. However, it includes a large variety of activities for component manufacturing and final vehicle assembly and a large diversity of vehicles[2]. To identify possible patterns of functional specialization, we complement the data with literature and analyze the subsectors at the level n-1. For these (C291, C292, and C293 groups), we have data for value added at factor cost and human activity (Eurostat, 2021b). The matching with National Accounts data at level n is explained in more detail in the Supplementary Material. There are significant discrepancies between databases in

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[2] Motor vehicles include passenger cars, commercial vehicles (vans, lorries and over-the-road tractors for semi-trailers), coaches, buses, trolley-buses, snowmobiles, golf carts, amphibious vehicles, fire engines, street sweepers, travelling libraries, armoured cars, concrete-mixer lorries, ATVs, go-carts and race cars. Also included are motor vehicle engines (other than electric ones) and chassis.

some cases due to the different methodologies and approaches used by the different statistical offices (see SM). These are related to the challenges of mapping functions and companies. Companies usually have more than one activity: principal, secondary, and ancillary (Eurostat, 2008). In some cases, such as in France, statistical offices allocate shares of companies according to the diverse activities, while in others they allocate whole companies according to the main activity. Due to this discrepancy, we have not included France in the analysis of subsectors (level n-1). These discrepancies are an issue that should be clearly stated and addressed by statistical offices to ensure comparability among countries. This also shows the diversity of activities that are carried out in companies and the diversification of the business in the automotive industry. The results will depend on to what extent ancillary activities are carried out within the company, the diversification of the activity and how statistical offices consider the activities.

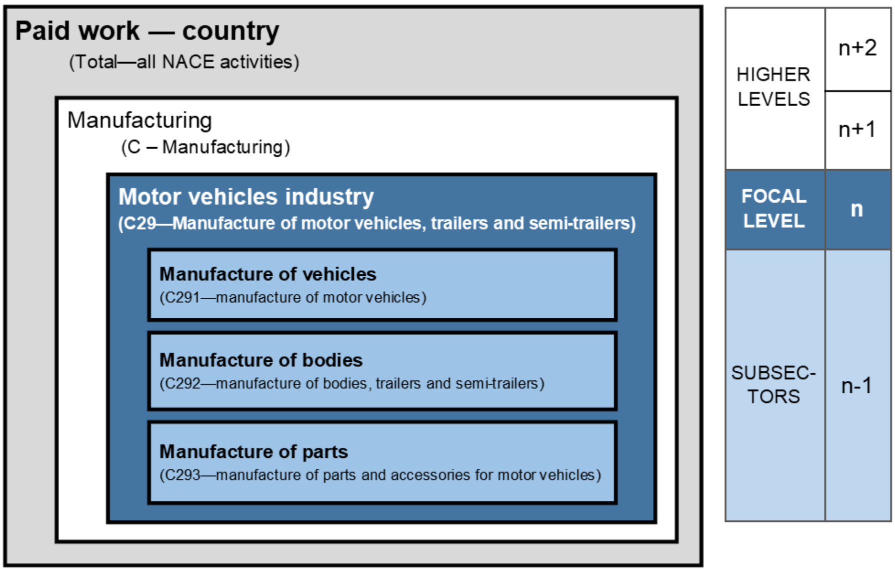


Figure 34 Levels of analysis of the paper.

The selection of countries was defined firstly by employment. We included those countries with more than 100Mh of work per year in the motor vehicles industry. For some countries that fulfilled that first condition, there was a lack of data for Energy Throughput: Slovakia, the UK, and Romania. This limited the selection of countries to eight (EU-8): Czechia, Germany, Spain, France, Hungary, Italy, Poland, and Sweden. The selected EU8 MVI represented in 2015: 77% of Human Activity, 82% of car production, and 83% of vehicle production in the EU27 (member states composition after 2020).

The analysis shows a picture of the state of the industry in 2018, a relatively recent year before the COVID pandemic. The exceptional measures taken for the Covid pandemic strongly affected the industry after 2020, which we do not aim to address.

6.3. Results

A summary of the quantitative results for each country for the year 2018 is shown in the End-use matrixes divided into extensive variables – i.e. quantities of flows and funds - (Table 7) and intensive ratios – i.e. flow-fund ratios - (Table 8). The following subsections present relations between diverse dimensions in time at different levels through graphs. The whole time series available for every variable in extensive and intensive terms are presented in the Supplementary Material.

Table 7 Extensive End-Use matrix of the Motor Vehicles Industry for the selected countries and the sum (2018). Percentages refer to the share of the total of EU-8.

	Population		Human Activity		Gross Value Added		Wages		GHG emissions		Energy Throughput electricity		Energy Throughput thermal		Car Production		Vehicle production	
	million	%	Mh	%	€ 10^9	%	€ 10^9	%	kton	%	TJ	%	TJ	%	thousand	%	thousand	%
Germany	82.8	25%	1277	39%	128.7	64%	57.2	67%	5241	57%	53.8	43%	67.5	54%	4894	41%	5449	38%
Czechia	10.6	3%	338	10%	9.2	5%	3.6	4%	297	3%	10.8	9%	9.5	8%	1409	12%	1414	10%
France	67.0	21%	165	5%	12.1	6%	5.4	6%	974	11%	16.6	13%	17.7	14%	1685	14%	2344	16%
Hungary	9.8	3%	215	6%	5.5	3%	1.8	2%	265	3%	6.1	5%	3.8	3%	464	4%	464	3%
Italy	60.5	19%	289	9%	17.5	9%	5.8	7%	419	5%	10.3	8%	8.7	7%	683	6%	1023	7%
Poland	38.0	12%	650	20%	6.0	3%	3.3	4%	333	4%	9.0	7%	5.7	5%	366	3%	654	5%
Spain	46.7	14%	258	8%	12.9	6%	5.2	6%	1499	16%	13.1	10%	8.8	7%	2169	18%	2833	20%
Sweden	10.1	3%	123	4%	10.5	5%	3.7	4%	201	2%	5.9	5%	3.4	3%	292	2%	345	2%
EU-8	**325**		**3315**		**202.4**		**85.8**		**9229**		**125.6**		**125.0**		**11960**		**14527**	

Table 8 Ratios in the End-Use matrix of the Motor Vehicles Industry for the selected countries and the EU-8 (2018)

	Economic Job Productivity	Hourly wage	GHG Emission Rate	Energy Metabolic Rate - Electricity	Energy Metabolic Rate - Thermal	Car Production Rate	Vehicle Production Rate
	€/h	€/h	kgCO_{2e}/h	MJ/h	MJ/h	cars/1000h	vehicles/ 1000h
Germany	101	45	4.1	42	53	3.8	4.3
Czechia	27	11	0.9	32	28	4.2	4.2
France	74	33	5.9	101	107	10.2	14.2
Hungary	26	8	1.2	28	18	2.2	2.2
Italy	61	20	1.5	36	30	2.4	3.5
Poland	9	5	0.5	14	9	0.6	1.0
Spain	50	20	5.8	51	34	8.4	11.0
Sweden	85	30	1.6	48	28	2.4	2.8
EU-8	**61**	**26**	**2.8**	**38**	**38**	**3.6**	**4.4**

6.3.1. Size in employment and number of vehicles

The main variables defining size and output in the Motor vehicles industry are Human Activity and vehicle production (Figure 35). By a considerable difference, the most prominent actor is Germany, with around 1277 Mh of employment and 5.4 M vehicles. With only 25% of the population in the EU-8, it represented 38% of the vehicle production, 39% of the working time, 64% of the Gross Value Added and 67% of the wages in the MVI in the EU-8 in 2018 (Table 7). This shows the centrality of Germany in the MVI of the EU-8 (and also EU-27).

The next-largest country in terms of Human Activity is Poland, with 650 Mh (20% of EU-8). However, the large employment does not translate in a large vehicle production (654 thousand, 5%), which is lower than in other countries with lower employment. In fact, Poland was only the 6th largest vehicle producer in the EU-8, with a very low Vehicle Production Rate (1.0 veh/1000h). This fact suggests that Poland does not devote itself to the final assembly of vehicles but rather to the production of parts. However, we are simply summing up the number of vehicles, no matter the type, and thus larger cars might be underrepresented. For a more thorough analysis of vehicle production, see Supplementary Material. Poland also has the lowest percentage of car production (56%).

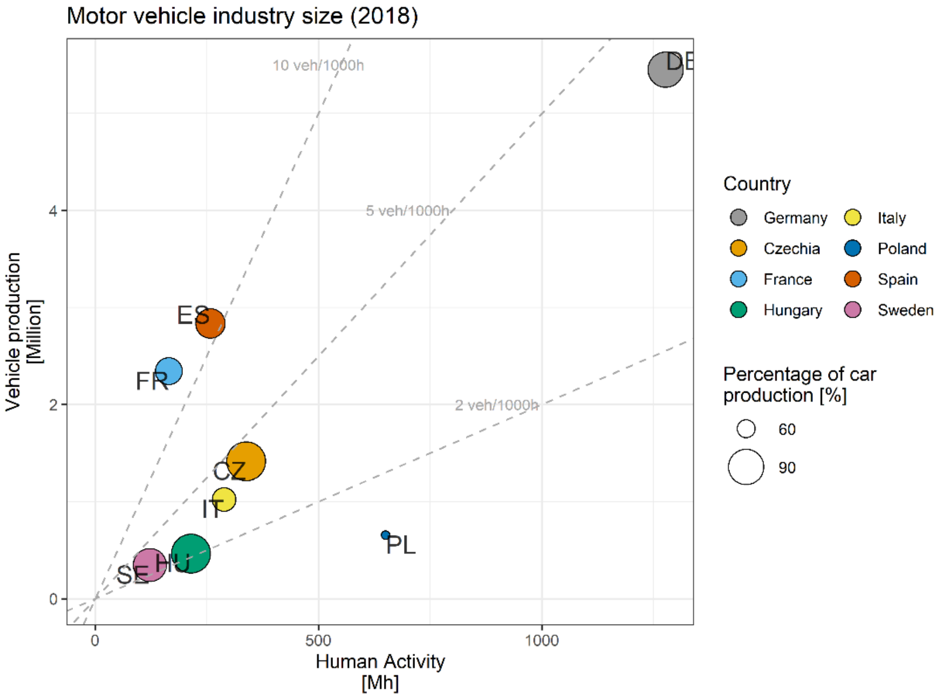


Figure 35 Human activity and vehicle production in selected EU countries (2018). The size of the circles is proportional to the share of car production in total vehicle production. Dotted lines define different levels of Vehicle Production Rate.

The country with the second highest vehicle production is Spain (2.2M - 18%), and third, France (1.6M - 14%). These are also the countries with the highest Vehicle Production Rates, above 10 veh/1000h. They do this at a lower level of employment (ES - 8% and FR - 5%) than Czechia (10%) and Italy (9%). The smallest country is Sweden, both in terms of production and work (0.3 M vehicles - 2% and 123 Mh - 4%), which also has the lowest population (10.1 M inhabitants – 3%).

6.3.2. Metabolic pattern within the national economy (levels n+1 and n+2)

We compare the MVI metabolic characteristics (level n) to each country’s paid work context (level n+2) and manufacturing (level n+1).

Employment

The share of MVI employment could be considered rather small (below 4% in all countries) (Figure 36), but we are in a context of great differentiation in the economic structure of countries. This large number of activities makes that each represents a small share. Exceptions are labor-intensive sectors such as services (e.g., education, healthcare, etc.).

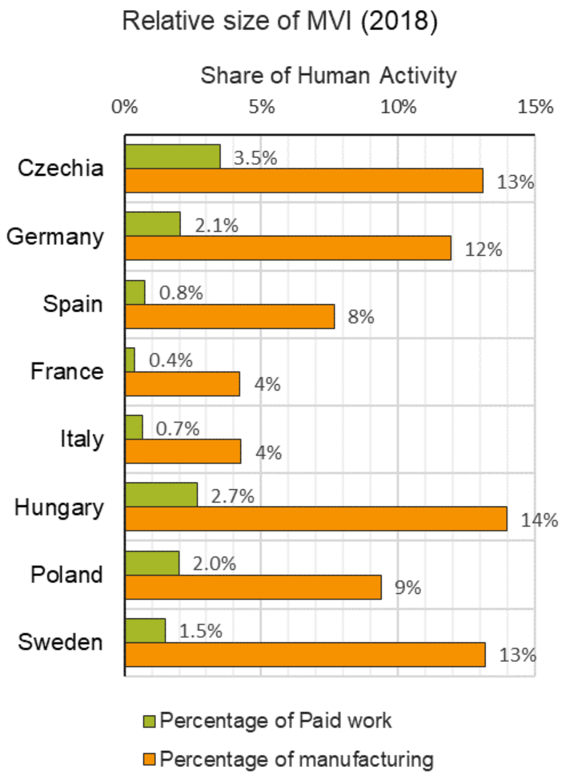


Figure 36 Relative size of the Motor vehicles industry within Paid work and Manufacturing for the selected countries (2018)

The country whose MVI employment is relatively higher is Czechia, with 3.5% of the workforce. In other words, we could say that it is the country that depends the most on the auto industry. Human Activity per capita in Czechia in MVI has almost tripled since 1995 (see supplementary material). After Czechia, there are Hungary (2.7%) and Germany (2.1%).

Czechia and Hungary are relatively small countries (around 10M inhabitants) but they reached similar or larger MVI working time than countries 4 to 6 times larger, such as Spain, Italy and France (47-67M inhabitants). On the one hand, Czechia allocated 338 Mh to the auto industry (3,5% of paid work), and Hungary 215 Mh (2.7%). On the other hand, large countries such as Spain 258Mh (0,8%), Italy 289 Mh (0.7%), and France 165 Mh (0,4%) have the smallest share of direct employment (less than 1%). Despite their significant percentage of the EU-8 population (14%, 19%, and 21%, resp.), these countries contribute relatively little to the working time in the EU8 MVI (8%, 9%, and 5%, resp.).

We can also analyze the weight of MVI within industrial sectors. Czechia, Germany, Hungary, and Sweden have around 12-14% of the manufacturing work in the MVI. In these cases, we can say that the MVI is a significant share of the local industry. In Spain and Poland, it represents 8-9% of the manufacturing employment. However, the Spanish MVI (0.8%) represents a smaller percentage of total paid work compared to Poland (2%). France and Italy have the smallest shares of MVI employment in the total paid work (0.4% and 0.7%) and, also, the smallest share for manufacturing (4%).

Metabolic rates

The flow/fund ratios of the Motor vehicles industry and the average of paid work are shown for every country in Figure 37: Economic Job Productivity, GHG Emission Rate, Energy Metabolic Rate electricity, and Energy Metabolic Rate thermal. These graphs tell how intensive a country's MVI is compared to the average of all sectors in paid work and manufacturing.

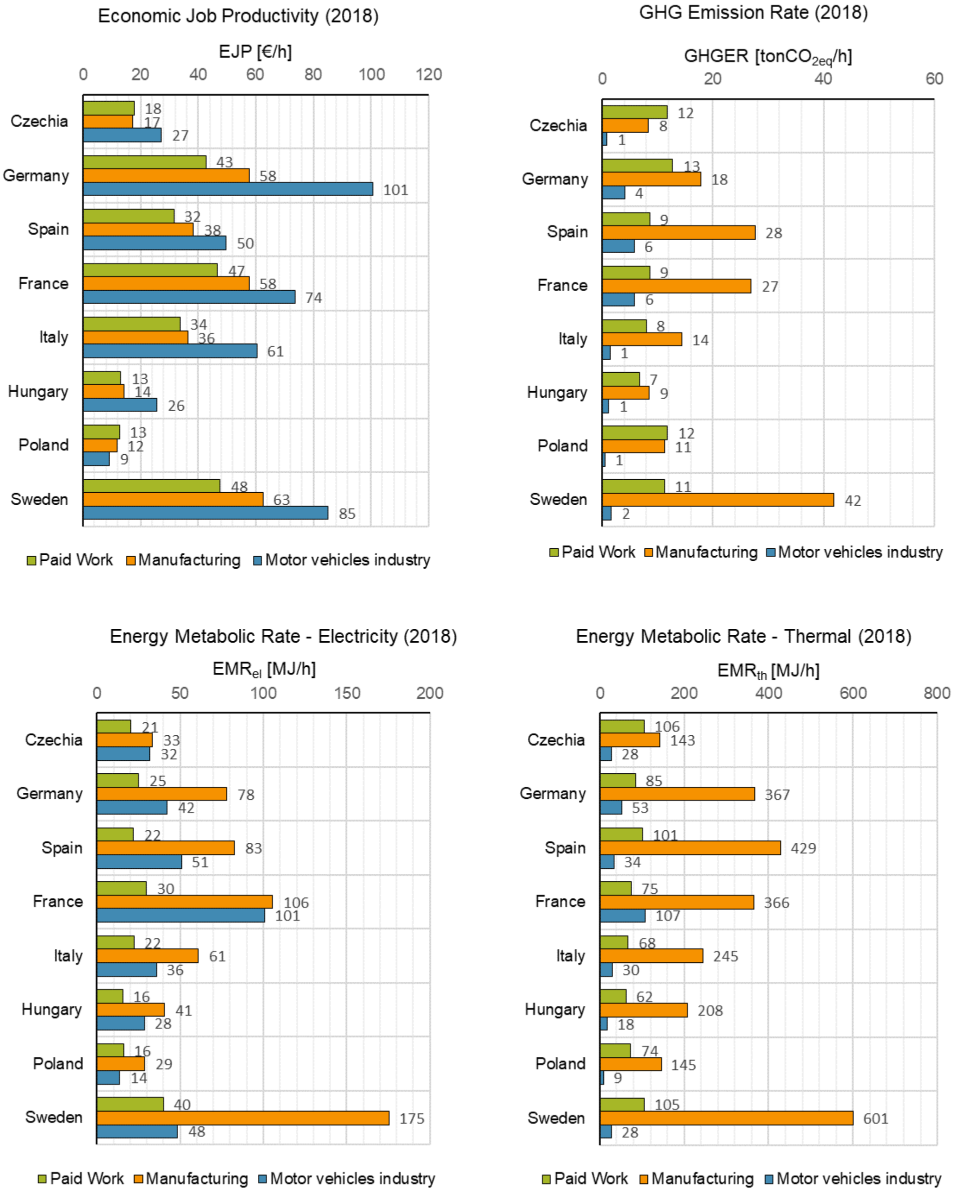


Figure 37 Comparison of flow/fund ratios for the Motor vehicles industry, Paid work and Manufacturing in 2018: Economic Job Productivity, GHG emission rate, Energy Metabolic Rate (electricity and thermal).

Except for Poland, the Economic Job Productivity of the MVI is higher than the average for Paid work and Manufacturing. In general, industries have larger metabolic rates (except Czechia and Poland) and for MVI it is even higher (except for Poland). The largest differences are found in Germany and Hungary, where the MVI EJP (101 and 26 €/h, resp.) more than doubles their average EJP for paid work (43 and 13 €/h, resp.).

In terms of direct emissions, the GHG Emission Rate is consistently lower in the MVI than in Paid work and Manufacturing. For countries like Czechia and Poland, this difference is especially significant. The GHGER for Czechia is 1 ton/h. These emissions are tightly related to the Energy Throughput Thermal, which is also lower in all countries in the MVI, except France. France has both electricity and thermal EMRs in MVI (101 and 102 MJ/h) higher than the averages of paid work (29 and 77 MJ/h). Being a final products industry with a high share of final assembly of vehicles, it is expected that the MVI is relatively less intensive in terms of direct emissions and energy than other more basic industries. The difference with manufacturing is larger in countries like Sweden, which has important *Pulp and Paper* and *Iron and Steel* industries, sectors with high energy and emissions intensity (Velasco-Fernández, 2017). This difference is especially clear with the EMR thermal in Sweden, which is 635 MJ/h for the whole of manufacturing and 13MJ/h for MVI.

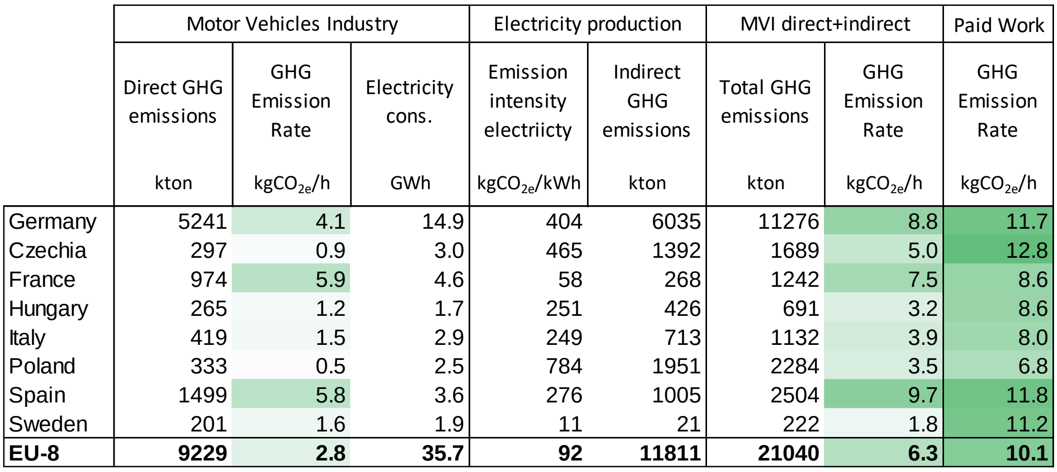
Except for Poland and Sweden, the EMRs for electricity in the MVI are higher than their average in paid work. The EMR of electricity in Sweden in MVI is even higher than most of the rest of the countries' EMR in paid work. At the same time, both MVI and Paid work EMRs are lower than those of Manufacturing. This indicates that the MVI is more electricity-intensive than other activities such as services but less than the rest of manufacturing. We should always consider that the indirect emissions in the energy sector could substantially increase the overall GHGER depending on the electricity mix.

In general, the MVI is fewer emissions- and energy-intensive and more intensive in work and value added than other industries. However, analyses from a global value chain perspective show that it induces emissions in upstream sectors (Alcántara and Padilla, 2020; Sato and Nakata, 2020; Yuan et al., 2018). The growth of this sector supported by more resource-intensive upstream processes abroad could generate the misleading conclusion of relative decoupling at the regional level. The direct emissions would rise less than the gross value added. In this sense, MVI would be a desirable sector to have in the national economy. This is only within the paradigm of production-based calculation of national emissions, not considering the effect on the global emissions in terms of upstream emissions and the subsequent use of the produced vehicles.

GHG emission rate

GHGERs (together with EJP) allow us to evaluate the effect of MVI in a potential decoupling. In all countries, the Paid work GHGER is larger than the one in MVI (Figure 38). In some cases, such as Czechia, Poland and Hungary, the difference is wider. For example, Poland in 2018 the general PW GHGER is about 6.8 kgCO_{2e}/h while MVI's is only 0.5 kgCO_{2e}/h. This shows the beneficial character of MVI in the national economy, with a rather low GHG emission rate and high Economic Job Productivity (EJP). We can see this lower GHGER compared to the average in each national economy even if we include indirect emissions in electricity production (Figure 39).

Figure 38 Emission intensity of paid work and motor vehicles industry for each country (2018). The grey dotted line indicates y=x.



	Motor Vehicles Industry			Electricity production		MVI direct+indirect		Paid Work
	Direct GHG emissions kton	GHG Emission Rate $kgCO_{2e}/h$	Electricity cons. GWh	Emission intensity electriicty $kgCO_{2e}/kWh$	Indirect GHG emissions kton	Total GHG emissions kton	GHG Emission Rate $kgCO_{2e}/h$	GHG Emission Rate $kgCO_{2e}/h$
Germany	5241	4.1	14.9	404	6035	11276	8.8	11.7
Czechia	297	0.9	3.0	465	1392	1689	5.0	12.8
France	974	5.9	4.6	58	268	1242	7.5	8.6
Hungary	265	1.2	1.7	251	426	691	3.2	8.6
Italy	419	1.5	2.9	249	713	1132	3.9	8.0
Poland	333	0.5	2.5	784	1951	2284	3.5	6.8
Spain	1499	5.8	3.6	276	1005	2504	9.7	11.8
Sweden	201	1.6	1.9	11	21	222	1.8	11.2
EU-8	**9229**	**2.8**	**35.7**	**92**	**11811**	**21040**	**6.3**	**10.1**

Figure 39 GHG emission rate of Motor Vehicles Industry (direct, and direct+indirect) and Paid Work. Emission intensity of electricity comes from EEA (European Environment Agency, 2021) *(2018)*

6.3.3. Metabolic patterns (level n)

In this section, we explore the relations between flow/fund ratios and their evolution for the Motor vehicles industry in the EU-8 countries. Figure 40 shows the Energy Metabolic Rate (EMR, in gross energy requirement per hour of paid work) against Economic Job Productivity (EJP, €/h) in 2018. The size of circles is a function of the total Human Activity and the dotted lines show reference energy efficiency in € of value added to MJ of energy throughput in GER.

The Energy Metabolic Rate is higher when the function is mostly manufacturing (instead of design and other ancillary services), and the facilities are automatized, requiring fewer workers for the production no matter the final product. However, automatization has not necessarily entailed a direct substitution of human labor by robots but more precise control of geometry and quality (Krzywdzinski, 2020). Also, automated machinery has not necessarily made work disappear but transformed blue-collar physical work into white-collar management and control. Even comparing manufacturing activities, EMRs can differ in the function of the specific processes. For example, the fabrication of engines in foundries is more energy-intensive than the assembly of cars.

Economic Job Productivities are higher or lower depending on the value assigned to the outputs. Engineering tasks tend to have higher value added, even though they tend to be time-intensive. The production of high-end cars will imply higher value added than smaller passenger cars. The allocation of activities and thus their value capture among countries depends on path dependency, power relations, and hierarchies established by the current international division of labor. We can see differences among EU countries here, but the EU industry has a relatively higher value added than the rest of the world, representing a relatively high share of its exports (Pérez-Sánchez et al., 2021).

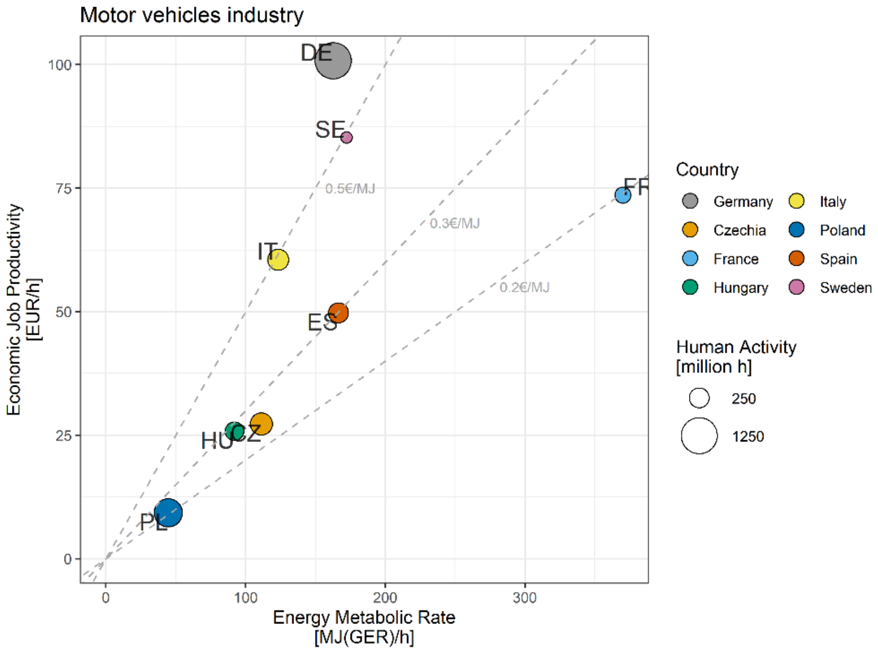


Figure 40 Energy Metabolic Rate and Economic Job Productivity for the motor vehicles industry (2018). Dotted lines indicate different levels of Economic Energy Efficiency (€/MJ). The size of the circles is proportional to Human activity.

There is a large range of values both for EMR and EJP. Poland has the lowest EMR (14 MJ/h electric and 9 MJ/h thermal), and EJP (11 €/h). On the other end, the largest EJP is that of Germany (101 €/h), 11 times that of Poland.

France has the highest EMR by far (electricity 101 and thermal 107 MJ/h), 7 and 12 times those of Poland and more than doubling the second highest, that of Sweden (55 and 28 MJ/h). On the other hand, France has only the third EJP (74 €/h). The French EMR might be affected by the selection of purely industrial activity in national accounts by its national statistic office. The working hours reported in SBS statistics double those in National Accounts (see Supplementary Material). This entails that an EMR calculated with the SBS working hours would be half of its present value, close to the level of Germany, Sweden and Spain. The problem is that functions do not map one-to-one to the institutional units that produce them, companies. Companies in MVI carry out many businesses including a wide range of vehicles and parts. They also devote themselves to services such as insurance and financialization (do Carmo et al., 2019). Statistical offices aim to select the primary activity or the minimum economic unit possible to allocate their value added and employment to that primary activity. SBS statistics in France allocated data from companies according to their main activity, whereas National Accounts disaggregated into minimum economic units to be able to allocate by activity more thoroughly. Data comes from Eurostat but the original compilation of data is carried out by each national EU member. In the case of France, we can see how National accounts select more specific disaggregated units, dividing industrial from other activities. This decreases the amount in the denominator of the EMR and thus increases the EMR.

Germany, Sweden and Spain have similar Energy Metabolic Rates, all over 160 MJ/h in GER. However, they do this at totally different levels of Economic Job Productivity. These range from 101 €/h in Germany, to 85 €/h in Sweden, to 50 €/h in Spain. While there is this set of countries that share EMR but not EJP, Hungary and Czechia have very similar EJP and EMR (around 25 €/h and 100 MJ/h). Also, Spain and Hungary have very similar energy intensities (0.3 €/MJ), but Spain doubles the EJP of Hungary.

Germany and Sweden have these large EMR and EJP with a rather low VPR (4 and 3 veh/1000h). This might imply that Germany centralizes the core development of vehicles. Development and innovation require more specialized and high-skilled workers, which generate more value added (higher EJP). On the other hand, large automatization or high energy-intensity activities in industrial specific activities might compensate this labor-intensive activity and maintain a high EMR. The differentiation of final products might also explain part of the broad range in EJPs.

Economic energy efficiency (EEE) is a very common indicator for economic and environmental analysis, despite its problems for assessing the multidimensional performance of countries and sectors (Fiorito, 2013; Phylipsen et al., 1997; Sorman and Giampietro, 2011; Velasco-Fernández et al., 2020a). In Figure 40, we can see how this indicator simplifies the information of two metabolic rates in relation to working hours (EMR and EJP), which explain the technological and value-added intensity of the sector. These two separate indicators have a clearer and more intuitive meaning than EEE, related to mechanization of activity and a proxy of hourly wages and income, respectively. In this example, countries with different EMR and EJP end up having the same EEE, such as Italy and France (around 0.5 €/MJ) and Spain and Hungary (around 0.3 €/MJ).

6.3.4. Subsectors (level n-1)

The Vehicle Production Rate at the MVI level provides some insights into the specialization in the production of parts or vehicles. In this section, we are getting down another level (level n-1), analyzing the subsectors in the Structural Business Statistics (Eurostat, 2021b): *C291 – manufacture of motor vehicles* (henceforth Manufacture of vehicles)[3], *C292 – manufacture of bodies, trailers and semi-trailers* (henceforth Manufacture of bodies), *C293 – manufacture of parts and accessories for motor vehicles*

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[3] Manufacture of vehicles includes motor vehicle engines and chassis (Eurostat, 2008).

(henceforth Manufacture of parts). We have data on Human Activity, and Value added at factor cost for these subsectors.

Figure 41 shows the different internal configurations of the MVI in the different countries: the share of Human Activity in the subsectors. All countries have less than 10% in the subsector Manufacture of bodies. The specialization in the subsectors Manufacture of parts or of vehicles determines largely the sector's overall metabolic patterns and functions at the level n. According to this, we can classify countries into three types: (i) oriented to Manufacturing of vehicles (higher than 60% for motor vehicles: Sweden and Germany); (ii) intermediate (between 40% and 45%: Spain and Italy); and (iii) oriented to parts (Hungary, Czechia, and Poland: around 75% for parts).

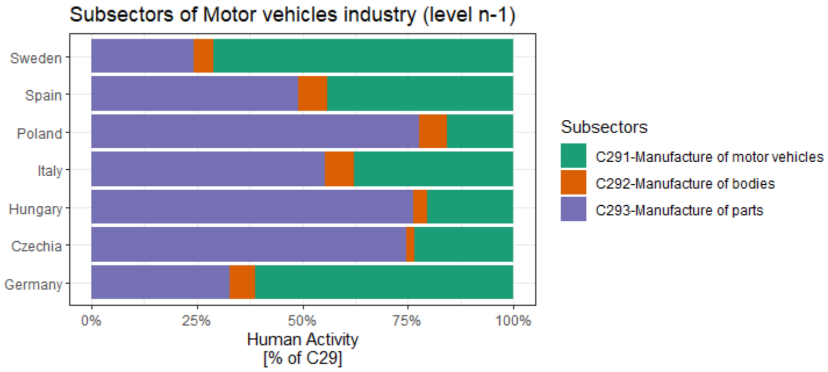

Figure 41 Shares of Human activity in the subsectors of the Motor vehicles industry (2018).

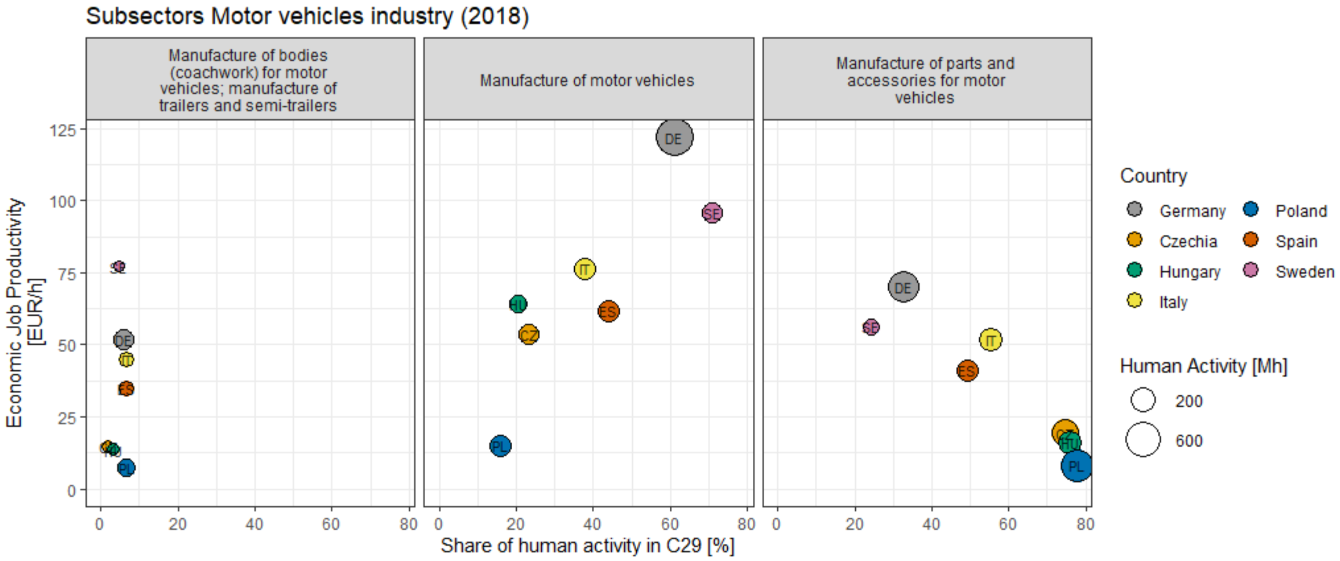

Figure 42 Economic Job Productivity by share of human activity of subsectors in the motor vehicles industry (2018). The size of the circles is proportional to Human Activity in the subsector.

Figure 42 shows the share of Human Activity in relation to the Economic Job Productivity in each subsector for 2015. The size of circles is defined in function to Human Activity. This sectoral disaggregation at level n-1 shows more clearly the divergence in value added per hour of work (EJP) for a more specific production stage. The functional clusters of countries go hand in hand with different patterns of EJP within the same subsector. For example, Sweden and Germany have similar shares of work in the subsector Manufacture of vehicles, and at the same time, they have the highest subsectoral EJPs. The largest EJPs are those for the Manufacture of vehicles, but at the same time they increase in function of the share of employment in that subsector. The manufacture of vehicles is the main activity of Original Equipment Manufacturers (OEMs), who have certain power over the activities of the whole supply chain.

3.4.1 Manufacturing of parts

Within the subsector Manufacture of parts, there is considerable variability in Economic Job Productivities. Motor vehicles have a great number and diversity of parts. We can classify them by value-added: high (e.g., engines and transmissions), medium, and low (e.g., wire harnesses and seats) (Domański et al., 2013). In this case, the three clusters defined by specialization in the subsector are also linked to different levels of EJP. Sweden and Germany are around 60 €/h and 30% of Human Activity in the Manufacture of parts, Italy and Spain around 45 €/h and 50%, and Czechia, Hungary, and Poland around 15 €/h and 75%. The EJPs of the Manufacture of parts in Sweden and Germany are even at a similar level to the Manufacture of vehicles in Italy and Spain.

We have seen in the previous section how Poland has the lowest EJP in the MVI. Here, we see that it has a large share of the subsector Manufacture of parts and systematically the lowest EJPs in all subsectors. But it is not only Poland. Czechia and Hungary also have the highest shares of jobs in Manufacture of parts and, at the same time, the lowest values of EJP in that subsector of all the EU8. They also have the lowest EJPs and a similar share of Human Activity for the Bodies and Parts subsectors. Their differences in the overall MVI EJP (level n) might be explained by the EJP in the Manufacture of vehicles (level n-1) in Czechia and Hungary, which more than doubles that of Poland, having roughly the same employment percentages.

3.4.2. Manufacturing of vehicles

The broadest variability among countries in Economic Job Productivities is in the subsector Manufacture of vehicles. For example, the EJP of Germany more than doubles that of Italy. Sweden and Germany have the highest EJPs (106 and 98 €/h, resp.). Czechia, Italy, and Spain have similar values for EJPs at around 45-55 €/h. This somewhat large EJP is similar to Hungary’s (around 75 €/h).

Apart from technology, these discrepancies might happen principally for two reasons: the differentiation of the product (production of higher-end vehicles) and the weight of the development of vehicles (engineering activities). Vehicle design is primarily developed in the main headquarters of OEMs, and the value capture of these activities is higher. These preproduction stages are at the initial peak of value added of the smile curve (Ali-Yrkkö et al., 2011; Del Prete and Rungi, 2017; Rungi and Prete, 2018), which indicates that preproduction (design and engineering) and final production and services (marketing, sales, etc.) have a larger proportion of value added than the rest of activities in the value chain. The production of premium vehicles and the core development of vehicles are activities with limited demand and require a certain reputation associated with particular companies.

Figure 43 shows the Vehicle Production Rate and Economic Job Productivity specific to subsector *C291 – Manufacturing of motor vehicles*. The size of circles is proportional to the share of car production in relation to vehicle production (cars, buses, trucks, etc.)

to consider the product mix. At the level n-1, we can approach the activities of design and final assembly of vehicles but only in terms of value added and employment. Unfortunately, we do not have energy or emissions data at this level. The VPR is the lowest in Sweden, Poland, and Germany (around 5 veh/1000h) and the highest in Spain, and Czechia (just below or over 20 veh/1000h). The differences between the largest VPR and the lowest are large, the Spanish one is about 5 times larger than that of Sweden. As we have seen before, Hungary has a larger EJP in the subsector C291-Manufacturing of vehicles despite having a lower overall EJP at level n (C29 - MVI) than Spain. The differences at the focal level n (C29) come from the larger differences in C292 - Manufacturing of parts, where Hungary, Czechia and Poland have very low EJPs (see Figure 42).

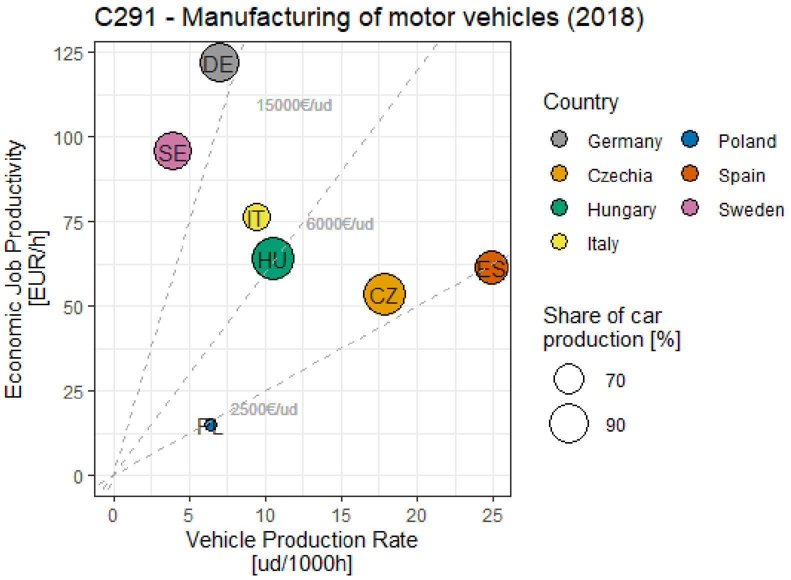

Figure 43 Economic Job Productivity against Vehicle Production Rate for the subsector C291 – Manufacturing of motor vehicles in 2018.

Dotted lines indicate different levels of Value added at factor cost by vehicle. Size of circles proportional to share of car production in relation to vehicle production [%]

There are a few factors affecting the VPR now that we analyze the specific subsector, and the production of parts is not distorting it. This subsector includes the production of engines and chassis (Eurostat, 2008). Therefore, a larger production of engines and chassis to export for other countries to assemble will imply a lower VPR. Also, mechanization and automatization require fewer work hours for the same production level and therefore imply a higher VPR. On the other hand, a high share of white-collar workers in core engineering and other ancillary activities results in a lower VPR. This might be the case of Sweden and Germany, which have the lowest Vehicle Production Rates but the highest Economic Job Productivity. Labor productivity is high in terms of value added, but it is not in terms of vehicle production. This is a sign that they might be capturing the value added in the whole production chain of cars in the core engineering design processes in OEMs headquarters.

Another factor could be the organization of tasks in the value chain, also related to the designs. Some vehicle designs might consist of larger modules with a more straightforward final assembly process and more complex in the fabrication of parts, entailing a higher VPR in C291. This modularization is intrinsically linked to vehicle design, company relations, outsourcing, and production processes (MacDuffie, 2013; Takeishi and Fujimoto, 2005). This would entail a higher VPR. This would require an analysis of the specifics of manufacturing processes, which we cannot assess with the available data at this level.

And finally, we must always consider the diversity of vehicles, which are all summed up for the VPR regardless of the type. Countries like Italy and Poland have a VPR between 5 and 10 veh/1000h but have the lowest car production shares (67% and 56%, respectively). LCVs, heavy trucks, and buses are larger than passenger cars; therefore, more time might be needed for their production. The product mix inherent to any sector at this level hinders the interpretation of VPRs.

6.4. Discussion

6.4.1. Metabolic patterns, roles, and hierarchies

Our analysis shows that the MVI is not a homogeneous sector in terms of its structural and functional characteristics. We can cluster the countries in three groups regarding specialization in subsectors: specialization in vehicle production (Sweden and Germany), in manufacturing of parts (Eastern countries: Poland, Czechia, and Hungary), and the rest of the countries (Spain, France, and Italy), which have an intermediate position and more heterogeneous metabolic patterns. It is not only companies that are hierarchically ordered depending on their tier, but also countries. A hierarchy of countries emerges parallel to that of companies, which depends on the type of companies they have. In this case, the differences in metabolic patterns are related to the roles within the EU27 auto industry division of labor.

Germany is the largest producer in terms of human activity, value added, and production, with the highest EJP. The relatively high Energy Metabolic Rates might entail that production processes are more energy intensive than in other countries due to automatization and the allocation of specific activities such as engine production. This German vehicle production per working hours at the subsector level is the second-lowest only before Sweden. Lower productivity in vehicles production does not necessarily translate to lower economic labor productivity. This is due to the fact that Germany specializes in manufacturing higher-end vehicles and parts and a substantial presence in engineering design and management tasks. As a result, Germany captures more value-added through labor-intensive white-collar work and by importing cheaper components from neighboring countries.

Sweden has the lowest population of the EU-8 countries. Also, it has the lowest production of vehicles, share and amount of working time in the MVI. Regarding subsectors, it has the highest percentage of working time in Manufacture of vehicles of all countries but with the lowest Vehicle Production Rate. This lower VPR can be affected by the importance of larger vehicles such as heavy trucks: 37% of the employees in MVI in Sweden were devoted only to heavy vehicles in 2015, and 29% to both light and heavy vehicles (Pohl, 2017). Therefore, even though 85% of the final production of vehicles are passenger cars, the production of heavy trucks (14%) and buses (1% of the units) might be more labor-intensive.

Both Sweden and Germany have high EJP and EMR despite having low VPRs. They also have the highest shares of employment in the subsector Manufacture of vehicles. At this n-1 level, we can see how these low VPRs are compensated by the large value added per vehicle produced. They have the highest EJP in Paid work, manufacturing and MVI of all the EU-8, showing the value capture of their whole economy. This fact shows the importance of carrying out this disaggregated type of analysis. Within the same economic sub-sector higher-income countries tend to specialize on those activities providing higher economic return.

On the other end, Poland has the lowest metabolic ratios systematically in all dimensions and levels. This indicates a low automatization supported by low labor costs. Despite having the second largest workforce in the analyzed countries, they are only the 6th producer of vehicles. Most Polish Human Activity in MVI is allocated to the subsector Manufacture of parts, which makes it a supplier country to other MVI who assemble the final products.

The location of the headquarters of Original Equipment Manufacturers is strategic. They control the value chain activities even though they do not perform them directly. Outsourcing activities to suppliers from these OEMs generates a hierarchical supply chain with a pyramid form with the diverse tier levels controlled at the top by the OEMs (Frigant, 2011). On the one hand, automobile nationalism and political pressure exist to maintain the final assembly of higher-end vehicles and headquarters in core countries and close to final markets. However, the chains are getting more fragmented in a search for decreasing costs and maximizing profits. At the same time, control is increasingly centralized in a reducing number of companies (from 42 independent automobile assemblers in North America, Japan, and Western Europe in 1960 to only 12 in 2005) (Nolan et al., 2008). The large factories and investments (fixed costs) and the complex engineering development for the construction of vehicles are economic barriers to entry for new brands or companies to take over, locking in the existing hierarchies. Given the different degrees of power and infrastructure, there is no level playing field and no easy chance to catch up or upgrade for the actors at the periphery.

The fall of communism and, afterwards and most importantly, the integration of Eastern countries in the European Union generated the conditions for the outsourcing of lower value-added activities through foreign investments to countries like Poland and Czechia due to their lower operating costs (Balcet and Ietto-Gillies, 2020; Frigant and Miollan, 2014; Krzywdzinski, 2014; Molnár et al., 2015). This has been chiefly in terms of labor-intensive component manufacturing and the production of sub-compact cars and lower segment vehicles (Krzywdzinski, 2014). The peripheral actors of the auto industry in the EU have shifted from Southern to Eastern countries (Gerőcs and Pinkasz, 2019; Lung, 2004) and generated a new spatial division of labor. Countries like Spain still produces more vehicles than Czechia and Poland despite their larger employment in the sector of the latter. This is mainly due to the different specializations in subsectors. Spain has a larger share of employment in the subsector Manufacture of vehicles, whereas Czechia, Hungary, and Poland have it in Manufacture of parts.

Czechia and Hungary are the countries whose MVI represent more share of employment in their national economies of all EU-8 countries. These two countries are at the system's periphery and have the most similar metabolic patterns of EU-8. Compared to most of the rest of countries, they have low GHG Emission Rates and Energy Metabolic Rates. Since wages are lower (also related to the lower EJPs), more labor-intensive activities are located in those countries.

In Spain, France, and Italy the direct employment of MVI contributes relatively less to the economy than in the rest of the countries. But since they are large countries, they rank high in production and employment in absolute numbers. Spain and France have the second and third-largest vehicle production in the EU8. France and Italy have been part of the Europe’s industrial heartlands, with two of the main historical regions of vehicle assembly: the Paris region and Piedmont. French and Italian carmakers have offshored the full production to Eastern European countries, while Germany has fragmented production internationally (Chiappini, 2012). While France and Italy struggle to maintain their position as core countries, Spain has upgraded from its previous peripheral position.

France has high metabolic ratios for all variables of analysis. It had the third-highest Economic Job Productivity in 2015 and the highest GHGER and EMR (both for electricity and thermal). However, it had the lowest share of Human Activity in Paid work of the EU-8. The motor vehicles sector represents only 0.4% of the employment time in France. France has halved its production from its 2004 levels (Guzik et al., 2020) due to the relocation of lower-end vehicles to Eastern Europe and Turkey through French investment (Pardi, 2020). Despite maintaining control of the process via companies, the EJP of France is lower than in Sweden and Germany.

Spain and Italy have intermediate Economic Job Productivities and share of the subsectors Manufacture of vehicles and parts. The EJP of the subsector Manufacture of vehicles in Spain and Italy is lower than in Czechia and Hungary when the latter have overall lower EJPs at the focal level (C29). The EJP of Manufacture of vehicles in Spain and Italy is even at a similar level to Manufacture of parts in Germany and Sweden. While in general, Manufacturing of parts has lower values than Manufacturing of vehicles. This hierarchy within the same function may show differentiation in the type of vehicles and wage differentials. At the same time, the similar EJPs at the sector and subsector level for Italy and Spain are given at very different Vehicle Production Rates. While they have similar amounts of working time in MVI, Spain almost triples the vehicle production of Italy.

Until the 1990s, Spain was the major low-wage periphery in the European auto industry. Foreign investments started in the 1970s and 1980s due to the relatively low wages compared to core countries in Central Europe (Pallares-Barbera, 1998). The rise in costs and the integration of Central Eastern European countries shifted the periphery eastwards (Krzywdzinski, 2014), and Spain has thus become an intermediate or pericentral player (Domański and Lung, 2009; Lung, 2004). Lampón et al. (2016) show the relocation of component production plants during the period 2001-2010 from Spain to mainly Eastern Europe (48% of total relocated jobs) and the increase of value-added, capital, and skill-intensive activities (e.g., mechanical systems for motorization, transmission, and braking). This might explain the relatively high Energy Metabolic

Rates. Spain is the second country in vehicle production and GHG emissions after Germany and in GHGER and VPR after France.

Nowadays, despite having an intermediate share of Human activity in the subsector Manufacture of vehicles, Spain has one of the highest Vehicle Production Rates (level n-1), but this does not necessarily reflect a large Economic Job Productivity. This indicates that it is likely that white-collar jobs in development and management in France and Spain are not as central as in countries like Germany or Sweden. Also, in general, salaries are lower. Sweden, Germany, and even Italy surpass the EJP of Spain. These three countries are more specialised in the subsector Manufacture of vehicles and have Vehicle Production Rates in C291 less than half those of Spain. Therefore, vehicle production is not necessarily liked to high EJPs.

Even though the local and sectoral perspective is limited in the context of open economies with great entanglement due to trade, regional characteristics can help us explain the countries' role in global production networks. This analysis can be complemented with a supply chain perspective, not assessed here but available in the literature (Fana and Villani, 2022; Timmer et al., 2015). The auto industry is a final products industry. Most of the GHG emissions and energy in the production of vehicles are emitted and consumed in upstream sectors (Alcántara and Padilla, 2020; Hardt et al., 2021; Jonsson, 2007; Sato and Nakata, 2020), while large shares of value added and employment are allocated in the automotive industry.

6.4.2. Methodological implications

The results flag three key points for economic analysis and sustainability: (i) the metabolic patterns of auto industries are different in large part due to functional and range specialization, (ii) the metabolic patterns of the MVI may produce the illusion of decoupling within the national economic structure, (iii) the criticalities of energy and material efficiency indicators. The multidimensional and multilevel analysis presented here contributes with valuable structural and functional information to avoid these misinterpretations, even if it requires to be complemented with more detailed information at lower and upper levels to have a full picture of the overall social-ecological system (Giampietro et al., 2021).

Some countries focus on producing intermediate parts, whereas others assemble the final products and manage the whole production. Methodologies of analysis should capture the diversity of fragmented production stages or functions within the value chain. The differences in production factors are not only related to different technologies, efficiencies, or productivity improvements (how the production is made) but also to the various stages within the same value chain (what type of product or activity), even implying the financialization and servicification of the auto industry. Moreover, even when considering the lowest sectorial disaggregation in manufacturing of vehicles or parts, we still can see differences that might be explained by the specialization in higher-end products or different types of vehicles and parts. NACE classification at the division level is still too broad to capture intra-industry heterogeneity, and segment and functional specialization related to intra-industry hierarchies and core-periphery relations.

These core-periphery relations and functional specialization limits the validity or meaning of approaches for calculating consumption-based resource use such as the technology-adjusted consumption-based emissions (Kander et al., 2015) or the domestic technology assumption in single-country IOT. Due to functional specialization, applying a sectoral-performance indicator of a certain country to all countries would represent only a part of the activities that are required for vehicle production. The activities in MVI are in fact related and dependent on one another to get the final product, in this case, the vehicles and replacement parts. This critique is in line with existing literature in Input-Output Models on sector aggregation bias and the pitfalls of the domestic technology approaches (Andrew et al., 2009; Arto et al., 2014a, 2010; Bouwmeester and Oosterhaven, 2013; Lenzen et al., 2004; Steen-Olsen et al., 2014; Tukker et al., 2013b). Yet these generally refer to even more aggregated and thus even more heterogeneous sectors.

Despite this sectorial metabolic pattern variability among countries, the auto industry is a light industrial sector of final products, with lower impacts and higher value added compared to other industries and primary sectors. Simplistic analysis of emissions may indicate that the emission intensity of a country decreases when it invests in MVI, similar to what happens to services (Henriques and Kander, 2010; Marin and Zoboli, 2017). A narrow production-based analysis can lead to flawed conclusions on decoupling, the environmental Kuznets curve, and structural change for sustainability. These ideas have been debunked previously in literature (Fiorito, 2013; Haberl et al., 2020; Luzzati and Orsini, 2009; Muradian et al., 2002; Savona and Ciarli, 2019; Stern et al., 1996). The inverted-U shape of the Environmental Kuznets Curve is related to the fact that developed countries specialize in the upper sectors in the smile curve, including the MVI and other management and office work. This has low impacts compared to the more basic processes from which the auto industry requires inputs to function. While the existence of this sector in the national economy might be favorable in value-added terms compared to the average paid work and manufacturing metabolic rates, it induces impacts in other sectors (generally carried out in foreign countries). In another sense, the production of internal combustion vehicles commits further emissions in the mid-term during the lifespan of the vehicles. Therefore, the existence and growth of this sector in a country provide value added with a relatively low environmental cost at the expense of leaking impacts to foreign suppliers with lower salaries and the commitment of longer-term emissions in the use of vehicle fleets. This is another perspective to unequal exchange (Hornborg, 2009; Martinez-Alier and Schlüpmann, 1987; Muradian and Martinez-Alier, 2001). The whole value-chain impacts of vehicle production might not even appear in local consumption-based accounts since the final products and parts are in part exported to global markets. In contrast, value added and higher-paid jobs remain in the country. The spillover effect in upstream processes must also be analyzed carefully. Further work should explore the linkages between countries in terms of trade to understand more fully the dependencies and the complete picture of the distribution of impacts and profits in the supply chain of the MVI in the EU.

The variability of metabolic rates among countries linked to functional specialization and the beneficial nature of the automobile industry within national economies are not visible through the analysis of mono-scale Economic Energy Efficiency. EEE is one of the most common and indicators for macroeconomic sustainability, which is generally analyzed isolated and at a single level (mono-scale and mono-dimensional). It does not present enough information for analyzing the reasons why a certain country or sector is apparently improving their sustainability in a decoupling framework, i.e., when they understand sustainability as the possibility of generating value-added with fewer energy carrier consumption. In general, EEE is used for confirming the decoupling hypothesis by its proponents when countries decrease their EEE, arguing that development entails sustainability (following the Environmental Kuznets Curve). This indicator thus is designed for the currently central question of whether further growth at the current is possible with less or relatively less energy and emissions, as if it was possible to analyze this without considering the existent power relationships and the production processes that generate goods and services. This indicator and a mono-scale vision does not help explore what kind of metabolic patterns and production processes are linked to certain levels of EEE. The use of this perspective and indicator obscures the real important question here: the analysis of the production processes, the needs of society and how these provisioning systems could change.

In this paper, what we see is that EEE (a flow/flow indicator) is in fact a simplification (a ratio) of two metabolic rates EMR and EJP (flow/fund indicators). The latter represent better external referents for the data. EMR refers to concrete typologies of production at the level of structural type and reflects the level of mechanization of economic activity. With EJP, we can see how some activities in some countries capture more value per hour of work, which depends on the core-periphery relations and their functional specialization.

The metabolic rates per human activity also give the importance working time deserves. The definition of working time as a fund gives us a definition of the size of the sector – i.e., the number of workers employed. The inclusion and centrality of working time is key to address employment issues that are fundamental for social and economic sustainability. When we include only part of the dimensions that are relevant for sustainability (be it economic or environmental), we will see only part of the picture. This shows the excessive simplicity of economic energy and emission efficiency (in MJ/€ and $kgCO_{2e}$/€) indicators when we compare them to the multi-dimensional and multi-scale biophysical performance. This kind of multi-indicator analysis based on biophysical basis of socio-economic activities has been flagged as necessary by other authors critically analysing decoupling (Haberl et al., 2020).

6.5. Conclusions

This paper presents a multidimensional overview of the metabolic patterns of the EU automotive industry across scales which shows functional specialization, hierarchies within the sector and different metabolic characteristics from motor vehicles industry in comparison to the rest of manufacturing activities and the average of paid work. The Motor vehicles industry still represents a relatively large share of industry in some countries in the European Union. The MVI is relatively value added intensive and low emission- and thermal energy-intensive. Therefore, its existence in the economic structure of a country might be favorable in terms of environmental and value-added performance compared to other industries, potentially generating the illusion of decoupling.

The European auto industry has core-periphery relations that arise in the metabolic patterns in all dimensions. Even belonging to the same sector, the characteristics of the industry in each country are very different due to their specialization in subsectors or processes, the segment of vehicles and type of parts, their levels of automatization, and wages. This intra-industry heterogeneity limits the validity of domestic technology assumptions or the use of “the best” metabolic patterns as universal benchmarks to be used as goals for the industry. Each country is playing a different role and all of them are necessary currently to produce vehicles, regardless of the technological improvements that could still be made.

Some countries like Germany and Sweden have metabolic patterns that flag their core function in the European automotive system. Both present low vehicle production rates, but they have a large value added per hour of work and a large share of working time in the subsector Manufacture of motor vehicles. Germany is the center of the EU auto industry both in intensive and extensive terms: with the largest employment, vehicle production, and value added per hour of work.

Poland, Czechia, and Hungary are peripheral countries. They are more specialized in producing parts and allocate less value added and energy carrier consumption per hour of work. This set of countries has some of the highest percentages of direct national employment in this industry. More specifically, Poland has the lowest rates (greenhouse gas emissions per hour of work, energy per hour of work, and gross value added per hour of work) and the largest share of work allocated in the subsector Manufacture of parts. Other countries like Spain, Italy, and France play an intermediate role. They have more diverse metabolic patterns but have in common a relatively small percentage of employment in the total paid work in each country.

Even though the local and sectoral perspective is limited in the context of open economies with great entanglement due to trade, regional characteristics can help us explain the countries’ role in global production networks. This analysis can be complemented with a supply chain perspective, not assessed here but available in the literature (Fana and Villani, 2022; Pérez-Sánchez and Aguilar-Hernandez, n.d.; Timmer et al., 2015). The auto industry is a final products industry. Most of the GHG emissions and energy in the production of vehicles are emitted and consumed in upstream sectors (Alcántara and Padilla, 2020; Hardt et al., 2021; Jonsson, 2007; Sato and Nakata, 2020), while large shares of value added and employment are allocated in the automotive industry (Pérez-Sánchez and Aguilar-Hernandez, n.d.).

This type of biophysical multi-dimensional characterization across scales prevents misinterpretation of decoupling effects by identifying how performance, type of production and role in the production chain affects overall use of resources and value-added generation. Further research is required to better understand the complex entanglements between process performance, their functionalities and resource use allocation in national accountings.

CONCLUSIONS

7. CONCLUSIONS

The main objective of the thesis was to explore the performance of socio-ecological systems through a metabolic perspective using the MuSIASEM framework, aiming to contribute to quantitative analysis and enabling a more holistic and interdisciplinary reflection of the option space for their future transformation to sustainability. Undoubtedly, this is an ambitious objective, and the resulting insights are more limited and specific in nature.

This dissertation has assessed some key relationships and factors in the viability of modern Western societies through three case studies that analyse: (i) the current state of the residential sector, (ii) the embodied working time in trade in the US, the EU and China and (iii) the automotive industry in a selection of European countries. The proposed analytical framework allows us to understand better the existing relationships and conditions and is the first step to reflecting on possible futures. This way, we have shown how the organisation in households and time use is key for social practices and therefore consumption. How the international division of labour and different value capture of sectors and countries define national and sectoral metabolic patterns. In general, the three case studies show in different ways the importance of the inclusion of all kinds of time use in sustainability analysis. These topics will be further discussed next.

Since I've explored many fields, dimensions and sectors, conclusions are both specific to the case studies and overarching. These are in no case a mere extrapolation or generalization from the specific research questions in the case studies, but they represent an abstraction exercise to contribute in a more general reflection. This more holistic perspective enables drawing parallels and finding connecting points. Systems are made of entangled and interdependent parts. While understanding a sector might be interesting, a partial view can overlook side effects and the exploration of different sectors at different scales allows to gain perspective. Some topics and concepts are the unifying thread of the different chapters. Therefore, this chapter is not a mere aggregation and repetition of conclusions in each chapter but also an effort to draw the links between them. These findings also include the challenges we have faced, the policy implications and the following steps that could be taken.

7.1. Chapter 4 – residential sector

In chapter 4, I presented a holistic overview of the metabolism and sustainability of the residential sector using MuSIASEM and practice theory. I also presented a list of possible measures illustrating the existence of trade-offs in diverse dimensions: energy carrier consumption and greenhouse gas emissions, materials, floor area, human activity, social organisation and institutions, finance and desirability. Even though including all variables in a single model is not feasible, a holistic understanding of household metabolism can help build coherent anticipation scenarios by selecting plausible hypotheses. Ultimately, this is a necessary step towards profound transformations to sustainability.

This chapter provides a broad overview of aspects affecting household metabolism. The main contribution here is the integration of many dimensions that are rarely found together. It connects many authors that could remain hidden in their isolated silos otherwise, making it easier for other fellow academics to find existent branches of research that might be unfamiliar to them and have a few references to follow the thread. Multi/inter/transdisciplinarity are often invoked terms. However, we must still learn how to put them into practice, and we need the time to collaborate and learn about different fields and methods. This is not only putting together information as it is often done in literature reviews, but also understanding the connections between the dimensions.

Approaching the sustainability of the residential sector merely as a technical environmental problem is insufficient. Therefore, we need conceptualisations that go beyond the material objects. The residential sector comprises families (units of organised individuals) and dwellings (within municipalities/urban forms). These have shaped each other over time, and now we have a long-lived residential building stock designed for the nuclear family, locking in household types, practices, and, ultimately, resource consumption.

As explained in the introduction, the analysis of the functions in a sector is vital and this also helps in going beyond the mere material objects. Here, we have analysed those carried out at home, and their close relationship to service sectors, changing their scale, quality, and employment status. Also, we flag the fundamental role of time in many dimensions (duration, synchronisation, speed, etc.), and we relate it to trends of social organization (individualisation of life), power capacity (ownership) and energy consumption.

This analysis has also provided a critical view of energy efficiency. Energy efficiency is considered one of the pillars of a sustainable future. For example, the European Commission has directives defining energy labels and certificates in devices and buildings. Efficiency is generally framed as the input/output ratio of the technical object, which is the easiest to quantify but still at this technical level has many challenges. However, the performance of the system depends on how objects are used. For example, a car will have a given fuel economy, but it is not the same if it is used by one person than if it is packed.

In this sense, sharing generates economies of scale in the currently very atomised household sector. However, this has important implications for the organisation of daily life and time use, requiring further coordination, and even new spaces, devices, access modes (individual ownership vs product-services or collective ownership) and rules. In this sense, we should learn social skills such as active listening, negotiation, and compromise. This de-individualisation could be done within households, increasing their size, generating communities outside paid work and as product-services. This broader concept of efficiency that would come with sharing clashes with the individualised, accelerated and time-pressured daily lives of people in Western countries. In addition to engineers improving technology and producing new devices, there is a need for social scientists to rethink institutions and cultivate new rituals and capacities that enable a more sustainable use of resources.

Within the merely technical aspects of materials and construction, there are also many challenges. One of them is the complex relationship between embodied, operational energy and emissions, and materials. Nearly-Zero Emission Buildings decrease operational energy for climatization at the expense of a larger upfront investment. We must also differentiate between actions for renovation and more innovative ones for new construction, which requires a previous examination of whether we really need new construction. For example, modular deconstructable buildings can be proposed for new construction, but new buildings made of reused modular parts from deconstructed buildings will take time to appear. The current stock did not consider the future of the materials and their end-of-life will be a challenge. The long life of existing buildings makes that the decisions taken in their design stage define the characteristics of the whole stock for decades. This inertia affects the characteristics related to both their use, household sizes and practices and to the engineering side. The changes that we have seen in the last decades are larger than those that we are going to see in the following century since the system is mature and deep structural changes are more related to a possible further growth than to changes to the existing structures.

And last but not least, we should not forget about the role of dwellings as an asset, the financial role of real estate and the weight in family budgets for rent or mortgage. This is a constraint to alternative and flexible dwellings and to the rearrangement of layouts of existent buildings, and a key condition for the investments that are required for renovation for energy efficiency and change of energy carriers of devices for climatization and hot water.

7.1.1. Future work – accounting of household metabolism

This work could be the basis for a multidimensional quantitative framework of the residential sector, which would have human time, power capacity and floor area as fundamental variables as described in the chapter, stemming from the MuSIASEM framework. This was the initial objective of this work. However, in my experience with numbers, this is not an easy task.

Household metabolism is an excellent example of some of the issues of quantification, comparability and incommensurability presented in the introduction. For example, defining a sufficient level of needs and services is a value-laden and, in many cases, difficult-to-quantify exercise. Then, we would need accountings of how much time is necessary for fulfilling that function. Also, despite we have a 24h/day budget of time per capita, this time can be “multiplied” by multitasking. A mother can watch a cartoon movie with their children, and this could be considered both leisure and care. Therefore, assigning time to tasks and generating a closure requires prioritisation of functions and a loss of information.

Another challenge is the accounting of energy, where some devices can use different energy carriers (e.g., boilers and climatisation) and have different scales, from a room (e.g., stove) to a whole city (e.g., district heating). Also, in many cases, each dimension follows its own taxonomy, posing challenges to harmonisation without oversimplifying the common taxonomy. For example, this happens when trying to link energy to time by specific activities with the available statistics in Eurostat.

A thorough accounting of household metabolism should be complemented by services in paid work and the potential to generate communities. Household activities are seldom performed solely at home. They are often complemented or even substituted by services. Understanding the functions currently carried out at home and the potential alternatives could give rise to an accounting that allows the inclusion of these alternatives and does not lock in the current configurations. However, defining the amount of time that is necessary to fulfil a need both within paid work and at home is a challenging task, which depends a lot on the quality of the service that is expected. It is not the same to have a sandwich than a two-course meal, or to have classes of 10 or 120 students.

Among other concepts, this chapter explores the ideas of “scripting” and “lock-in” that long-lived infrastructure pose in socio-ecological systems. The design of dwellings constrains its possible uses, having a certain number of rooms (determining household sizes) and type of devices. The analysis of lock-in, stranded assets and committed emissions has already been explored for the energy system (e.g., coal power plants, refineries, etc.) and for industrial facilities (e.g., blast furnaces for iron and steel). Analyzing these phenomena in the residential built environment opens the door to multiple research questions related to changes both at the dwelling scale, regarding changes to layouts and the social organisation in households, and the urban form scale, switching suburban sprawl to more dense or rural configurations. These changes would transform deeply socio-ecological systems but come with material and other resource investments and deep cultural changes and clash with the current role of real estate in the economy.

7.2. Chapter 5 – embodied working time in trade

Chapter 5 contributes to the literature on consumption-based accounts with a multidimensional perspective, including the effect on national metabolisms analysing the sectoral structure of the economy.

In sustainability analysis, human time is a crucial and overlooked societal limit. Some core countries overcome their national time budgets and preserve their socio-economic structures by using energy and importing working time embodied in products and services. More specifically, this paper analyses the roles of the US, the European Union and China in the international division of labour by calculating working time in production, consumption, and trade in absolute and per capita terms for different subsectors in 2011. We could see how the greatest share of the workforce in China was still in agriculture. In contrast, the US and the EU had it in the tertiary sectors by outsourcing large shares of agriculture, mining, and industry: they import about half of the labour time into their consumption. The level of trade of embodied working time is proportionally larger than the one in GHG emissions, which is normally the one taking the spotlight. This is also due to the higher technological intensity of industrial EU exports, while the contrary happens to imported products. Lower wages are related to lower mechanisation and therefore lower emission intensity.

The zero-sum game of embodied time in the globalized economy entails the existence of winners and losers. This limited availability of time questions the long-term viability of the current pattern of development enjoyed by the EU and the US and the possibility for emerging economies such as China to complete a similar transition to a post-industrial economy. If China follows the development trajectory of other countries, the exported embodied time would increase within the exporting countries, raising the pressure on their time budgets. In conclusion, we can see how the different valuation of time and work depending on the country is a key characteristic of the global economy and a driver of development. We have normalised this situation, but if we consider that a task corresponds a value, it makes no sense that a bus driver in Norway earns many times the wage of a bus driver in India. The Norwegian worker will be able to purchase way more goods and services in global markets than the Indian one. Ultimately, this uneven valuation sustains Western higher consumption.

This shows how the global economy works as an organism where countries work almost like organs with specific functions. Local consumption is disconnected from local economic structures in developed countries. This is, Western countries have purchasing power over global markets, but at the same time this has generated material dependencies. Many tasks in material extraction and transformation are carried out elsewhere. This is true both for superfluous consumption and also for basic infrastructure and devices such as the key technologies for the energy transition (Bobba et al., 2020).

The specialisation in developed countries of service and office work represents a generator of income to acquire products made elsewhere with cheaper labour in global markets. Work is also a generator of identity. People in certain countries are far from material extraction and transformation. This affects their expectations and the perception of the material base of the economy, at a time when a reindustrialisation or ruralisation might be needed. For many people in developed countries, goods appear on the shelves of shops or even get to the door of their homes without participating in their manufacturing, or even without knowing anyone directly involved. Also, the knowledge and skills that the current workforce got in universities for office work might not be suitable for a transition to an economy relying on more blue-collar work.

In this case study, we analysed mainly working time, which explains the organisation of tasks regionally. Globalisation is materialized in infrastructure and buildings. Global production networks and the current large level of globalisation have been built through public and private large investments: ports, factories, railways, etc. Reshoring of economic activity in EU countries would require investments in infrastructure, the generation of stranded assets and possibly an increase in costs due to local salary standards and minimum wage regulations. In this sense, power and production capacities, another fund according to Georgescu-Roegen, are fundamental information that should be available and included to do an analysis of current characteristics and possible future transformations of provisioning systems.

7.2.1. Link to chapter 4 – human time at different scales

We can link the time-pressures in developed countries explained in the household sector in Chapter 4 and the embodied working time imports from Chapter 5. Paid work is the interface of the 24h/day budget of many adults and global production networks. The time at work (duration and synchronisation) is a huge constraint to the daily lives of waged workers, and also generate a certain income and identity to the worker. Working time causes strong scheduling in the daily lives of many adults, setting the conditions for the organisation of the rest of tasks to carry out in a day. Compared to the rest of the world, the working time per worker in the EU is low. Moreover, people in the EU spend more years in education and have an earlier retirement than the rest of the world, and the share of retired population increases due to its demographic structure.

The national economy and its position in the international division of labour defines its purchasing power in global markets. The working time trade balances complement the national requirements of working time and ultimately the daily lives of people. A net import of time releases pressure on time budgets and allows these societies to further increase or maintain their complexity. This means that they can carry out more activities or the outcome of activities carried out elsewhere in imported good and services. At the same time, they spend less time in paid work and more in retirement and education. Among them, this imported time in goods allows to provide non offshorable services that define welfare such as education and healthcare, and the possibility to devote to the type of employment that generates more value added in the international division of labor such as specific niche industries and office work in management and finances.

This happens despite the time pressures experienced by many people, especially working adults with caring responsibilities. Time policies have taken centre stage these last years. We now have the concepts of ‘right to time’, time poverty or time deprivation. The 4-day (32 h/week) workweek is considered one key measure to decrease unemployment, time pressures and environmental impacts at the same time. We should address, of course, the time pressures in developed countries, and the double shift of care activities. However, we should keep in mind that right now the economy in developed countries depends on net imports of embodied time in trade. While we reorganise time uses in Western countries (i.e., a redistribution of all kinds of work), we must consider the reorganisation of the economy to rebalance these international dynamics.

Another alternative to decrease time pressures is to bring closer the activities in daily life. The concept of 15-minute neighbourhoods and cities is currently gaining popularity. Paid work presents the greatest challenge in terms of increasing proximity to households even in dense cities such as Barcelona. On the one hand, the long-lived built environment poses a strong lock-in and these structural conditions constraint distances (more in suburban sprawl). On the other hand, policies could force or facilitate hiring of workers that live close to workplaces or have easy access to public transport to those workplaces, a structural rationalization of home-work distance.

7.2.2. Future work – time-energy metabolism

These two chapters are the first step towards a time-energy metabolism of countries that integrates and characterises households, national metabolism and the international division of labour. I am interested in further exploring the link from the daily lives of people to the macro aspects of the economy and bridging the great gap between atomised households and the enormous structures in paid work. This way, we could have a more informed discussion about the (i) distribution of unpaid work and the relation to services and welfare state, and (ii) an analysis of the national and international budgets of time.

The distribution of all kinds of unpaid work relates work in households (unpaid or in many cases shadow economy) to the welfare state and services in paid work. For this, it would be interesting to have accounts of the time, devices and energy needed for diverse activities in different configurations inside and outside paid work. For example, cooking at home vs cooking in restaurants and canteens. Available time use surveys use too broad concepts for this kind of analysis and do not assess household units, but individuals. Services should be thoroughly accounted in terms of specific output such as number of meals served, tourists pernoctations, years of education provided, etc.

The analysis of national budgets of time the contributions of local population to paid and unpaid work, the imported and exported embodied time. These are powered by different levels of power capacity and valued with different levels of wages. This would help in the debates on retirement age, needs of higher education and delay of entrance in the workforce, gender division of labour, distribution of work and cuts in working week and also about care work.

The matching of different databases related to time pose challenges. For example, I attempted to make an analysis and quantitative framework with paid work with National Accounts (hours declared by companies) and time use surveys (a thorough survey accounting of the time that people declare they spend on each activity for a certain number of days or weeks). However, what I found is that the numbers do not match. There are a number of possible causes: shadow economy, over/underestimations, timeframe of time use surveys only taking data from a part of the year.

7.3. Chapter 6 – EU automobile industry

Chapter 6 is a multidimensional and multilevel assessment of 8 European automotive industries via the End-Use Matrix tool from the MuSIASEM framework. It is an application of an existent tool that is yet to be fully explored, the end-use matrix, to a given industrial sector. We have analyzed the differences in this industry between countries and within the national economies. This has entailed an effort in generating alternative visualisations that show the complexity of key metabolic relations at different scales.

We study the nexus of the following variables: working time, value added, GHG emissions, electricity, and thermal energy. According to this nexus-metabolic characterisation, we can cluster the countries according to their functional specialisation in manufacturing intermediate parts and modules, final assembly of vehicles, and management and engineering design. This representation provides insights into the core-periphery dynamics in the European spatial division of labour and has implications regarding the possibility of structural changes for sustainability.

Core countries like Sweden and Germany specialise in management and design tasks, and are favourable in terms of value added. They have high value added generation per hour of work compared to the average of the economy and the rest of countries. Somehow paradoxically, value added is not related to the number of vehicles produced. Italy, France and Spain have an intermediate role. On the other end, Poland, Czechia and Hungary are more specialised in the production of parts, and this explains (and at the same time it is explained by) their lower economic job productivities.

These differences are also in part reflected in the divergence of methods in statistics, where at least France took a different approach. Companies carry out many activities, and allocating the resources, profits and impacts in the sectoral classification is challenging. In the example of the motor vehicles industry, there are many management and engineering tasks that are directly related to vehicle production, but there might also even be other activities more related to finance, insurances, etc. Both types of activities could be included in (C29) Motor Vehicles Industry or their more specific divisions in services (e.g., M71-*Architectural and engineering activities; technical testing and analysis*), depending on the main activity of the company. The inclusion of diverse dimensions and data is generally a challenge, and it is difficult to find transparent methods that describe the scope of the data, more when we use data from different countries with different statistical offices, despite the existence of common procedures.

When we explore economic sectors in paid work, we face a lack of information. While companies keep track of all their processes, inputs and outputs, this information is not available for researchers. This has also an effect in the aggregated available data in Eurostat. For example, when countries are very small and there are a very small number of companies in a sector, we lack data due to confidentiality. Safeguarding information is one of the pillars of competition, limiting the potential role of academia. We could analyse the annual reports of the leading automotive companies, but still this does not disclose the specific information of production processes and many activities are outsourced within the same sector.

7.3.1. Link to chapter 4 – from a narrow concept of efficiency to sufficiency and performance

At first sight, these two chapters might seem to have nothing in common. However, they both question narrow definitions of energy efficiency and flag the importance of a thorough analysis of functions and of a broader concept of performance. Energy efficiency is currently one of the main approaches to sustainability from policy. On the one hand, we have all the energy efficiency labels and certificates for appliances and buildings. On the other hand, Economic Energy Intensity has been one of the main indicators for macroeconomic sustainability policy.

One of the most common definitions of efficiency is to provide the same service with less output. However, it is difficult that the output, be it in a sector or a function, is exactly the same or comparable. For example, if we address food preparation, we could have a Michelin restaurant 20-course dinner, a perfectly managed Taylorist McDonalds burger or a steak quickly defrosted and grilled for Monday dinner after a long day of work. These outputs are all food, but have different social meanings and qualities, and they require different equipment, money, skills, time, energy and food products. Also, the same output can have different requirements depending on the social organization: it is not the same requirement per capita to prepare a lasagna for one person than for 10. However, the economies of scale of cooking for more than one person entail a higher social organization and commitment. This shows the simplified framework of efficiency when we should talk about "production recipes" (here, quite literally) of coherent bundles of flows and funds. But first, we should analyse which are the needs that these production recipes should fulfil. This is a value-laden exercise that needs participation. When we address needs is when the concept of sufficiency appears. Then we could explore possible social-technical organizations which could provide them.

The difficulties of having the same function for making indicators comparable also happen at the scale of sectors (and also countries). The example of chapter 6 shows us how an overarching sector such as Motor vehicles industry is made of fragmented production processes that happen in different countries. Therefore, the metabolic rates of the same industry in each country will reflect its functional specialization, tightly related to the position of the country in core-periphery hierarchies. It is not the same to devote oneself to engineering and development than to manufacturing of the cheaper parts. Nevertheless, all tasks are necessary to produce vehicles. Therefore, we cannot choose a "most beneficial metabolic pattern" from a group of countries and make it the benchmark goal for all countries. For example, we see how Germany has a high value added generation per hour of work, but this depends on the externalization of certain stages of production to Eastern European Countries. To have an exhaustive idea of the requirements and characteristics of motor vehicles industry, we should examine the tasks carried out at a lower level.

Moreover, at this level of analysis, the most frequently used indicator for energy efficiency is Economic Energy Efficiency (€/MJ). The different valuation of working time depending on the task and the country that performs it is generally not considered. This fact makes that countries that are capturing more value added are suddenly "more energy or carbon efficient". This indicator thus is designed for the current central question of whether further growth is possible with less or relatively less energy and emissions, as if it were possible to analyze this without considering the existent power relationships and the production processes that generate goods and services. These issues are not visible with EEE. Metabolic ratios that include working hours such as EMR and EJP have a much richer explanatory power.

7.3.2. Links to chapter 5 – International division of labour

In chapters 5 and 6, we find hierarchies of countries that are reflected in their metabolic characteristics due to the international division of labour. This time, we find them even within the same sector. The current economic system is so complex that there are thousands of different activities, and at the division level, there are still many activities. Even with the same activity, such as the production of cars, we can find that by changing the characteristics of the product, such as its segment, the metabolic patterns of the sector will likely be different. These sector fragmentations make it very difficult to compare sectors between different countries or allocate responsibilities for environmental burdens to certain activities, as all of them are strongly entangled.

7.3.3. Future work – global value chains in the automotive sector

The motor vehicles industry is one of the most relatively important industries for jobs and value added in developed countries, while it generates relatively few emissions and uses little energy. The motor vehicles industry is a final products industry. Its suppliers perform the more emissions- and energy-intensive activities. In this sense, chapter 6 does not address the whole value-chain impacts and profits of vehicle production and material entailments with other sectors.

Therefore, future work could explore the entire weight of motor vehicle production and check the value-chain impacts of this industry, which currently has political influence and government support. This is important considering the material, emission and energy models that conclude that a reduction in vehicle production and use might be fundamental. This kind of analysis could also include the regional distribution of value added and other economic profits across the value chain, to see how the production of value added in EU countries due to vehicle production is related to impacts and value added generation elsewhere.

The automotive industry is transforming along with the expected transformation of the fleets, which includes changes in materials, powertrains and a potential downsizing of the industry, which is suggested as fundamental by diverse vehicle fleet models due to material and GHG emission limits (de Blas et al., 2020; Garcia and Freire, 2017; Pulido-Sánchez et al., 2022, 2021). This downsizing would affect the Motor vehicles industry as well as upstream sectors (iron and steel and plastics, for example) and, therefore, potentially affecting the whole economy significantly.

7.4. General conclusions

The final objective of sustainability is not to reach a specific emissions target by 2050 but to transform the economy in a way that keeps running while respecting environmental and social limits. This is, clearly, a way more ambitious challenge. This means that the structures and organisation of society should change in order to allow the maintenance of its functioning in the long run providing good living conditions and decreasing pressure on the ecosphere.

To achieve this, first, we must move away from the conventional paradigm of economics to that of bioeconomics, where we analyse functions and the biophysical basis of processes and not only monetary flows. We should think about countries in terms of metabolism, as in organisms, by analysing the complex relation between functions and structures. In many cases, policy is focused on simply substituting structures, for example, with targets and subsidies for the electrification of private car fleets. However, we should think beyond the same objects we see now. Having in mind the overall function or need to fulfil, we can think about different organisations and devices that could fulfil the same purpose.

One key question in the sustainability debate is whether further growth is possible while decreasing resource use and impacts to the environment. In this sense, the analysis of how value added is generated becomes essential. The question of GDP and value has a wide literature that I have not detailed here. In this dissertation, we have seen how the assignation of value to tasks depends on many “arbitrary” questions. Some relevant ones are the allocation of a function to households (unpaid work), or to public or marketed services (waged work), the role of dwellings as an asset and housing bubbles and the value capture of countries and sectors within the international division of labour (role of unequal exchange).

Sustainability is a field on the interface between science and policy. Therefore, the work that I have done is also linked to existing policies and proposals that I have addressed in the previous sections of the conclusions. One key message for policymakers and society in general is that we cannot expect silver-bullet technical solutions. Instead, we should acknowledge the dilemmas faced, which require compromise solutions through a debate including diverse perspectives from stakeholders. There are plenty of trade-offs and side effects associated with each policy issue, and we have to learn how to explore them as much as possible.

We should learn how to communicate all this complexity and generate a healthy public debate and fair deliberation over sustainability, but in this sense, I cannot provide any specific direction or strategy. Everyone working in sustainability, after acknowledging the challenge of desirability, has their own ideas or intuitions of how communication, actions and social involvement should be effectively done. In many cases, conversations at work, during lunchtime, after seminars or in conferences end up revolving around desirability. We ask ourselves whether people will accept or not the changes that are necessary for a sustainable future. These changes go from constraining or (self)limiting consumption, changing routines to a major reshuffling of social organisation. Ultimately, this should be translated into policy action that can be effective and accepted. Therefore, in this thesis, I have been considering actions that potentially change the daily lives of people, but I did not examine whether these would be favoured by society, how they should be communicated or put in practice.

Regarding the methodology used in the dissertation, MuSIASEM is an accounting framework that is open and allows for a reflexive selection of categories. This enables the participation of stakeholders to decide which categories and dimensions are relevant. Nevertheless, these are limited by existing databases and statistics. The diversity of theoretical approaches from which it feeds (some of them explained in the introduction), nurtures the discussion and enables us to perform transdisciplinary analysis. The multi-scale perspective contextualises the metabolic patterns of sectors and countries. The simultaneous use of technical, economic, social, demographic and ecological variables avoids tunnel vision and increases the robustness of numbers. This robustness is built on the coherence that must be kept in the many connections across levels and dimensions, the Sudoku effect. Nevertheless, dealing with multi-dimensional information allows the analysis of trade-offs, but makes its data gathering more time-consuming and its operationalization more complex.

Within MuSIASEM and in this dissertation, time is one of the main variables that vertebrates socio-ecological systems. The epistemological conceptualisation of time as a fund in the economy provides its rightful space and flags its characteristics: agency, definition of a biophysical limit and the size of systems. The analysis and centrality of working time puts issues such as employment, unpaid work and just transition at the centre of the analysis. Unlike with money, it allows the inclusion of all activities, from households to global production networks.

One of the fundamental and cross-cutting themes of this dissertation is the nexus between time, energy flows, and power capacity. We see how the efficiency that has driven the evolution of modern societies is that of reducing time use (speed and power) rather than energy efficiency, the one which should tend to conserve resources. The capability of compressing time and effort by using power capacity (fuelled mainly by fossil fuels) has increased the complexity of socio-ecological systems and generated formidable lock-ins. This means that more activities are carried out and this is especially true for developed countries, who moreover enjoy net imports of embodied time in trade. In counterpoint to this social acceleration, scholars such as Georgescu-Roegen (1977) and Meadows (1996) have flagged the importance of slowing down. As with most changes for sustainabilty, this deceleration cannot happen only via individual behavior. While some people could take individual action towards a slowing down of daily life, deceleration should be increasingly accepted by society and should be guiding policy that leads to structural changes and therefore enable general changes in social practice.

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9. Appendixes

9.1. Appendix for chapter 4

Eurostat	
TOTAL - Total	
AC0 - Personal care	
AC01 - Sleep	Own care
AC02 - Eating	Own care
AC03 - Other and/or unspecified personal care	Own care
AC1_TR - Employment, related activities and travel as part of/during main and second job	
(Calculated) AC1_TR - AC913	Paid work
AC1A - Main and second job and related travel	
AC1B - Activities related to employment and unspecified employment	
AC2 - Study	Education
AC21A - School and university except homework	
AC212 - Homework	
AC22 - Free time study	
AC3 - Household and family care	
AC31A - Food management except dish washing	Unpaid work
AC313 - Dish washing	Unpaid work
AC321 - Cleaning dwelling	Unpaid work
AC32A - Household upkeep except cleaning dwelling	Unpaid work
AC331 - Laundry	Unpaid work
AC332 - Ironing	Unpaid work
AC33A - Handicraft and producing textiles and other care for textiles	Unpaid work
AC34A - Gardening; other pet care	Other
AC342 - Tending domestic animals	
AC343 - Caring for pets	
AC344 - Walking the dog	
AC35 - Construction and repairs	Other
AC36 - Shopping and services	Unpaid work
AC38A - Childcare, except teaching, reading and talking	Unpaid work
AC38B - Teaching, reading and talking with child	Unpaid work
AC37_39 - Household management and help family member	Unpaid work
AC4-8 - Leisure, social and associative life	Leisure
AC41 - Organisational work	
AC42 - Informal help to other households	
AC43 - Participatory activities	
AC51A - Visiting and feasts	
AC51B - Other social life	
AC52 - Entertainment and culture	
AC53 - Resting	
AC611 - Walking and hiking	
AC6A - Sports and outdoor activities except walking and hiking	
AC733 - Computer games	
AC7A - Computing	
AC7B - Hobbies and games except computing and computer games	
AC812 - Reading books	
AC811 - Reading, except books	
AC82 - TV and video	
AC83 - Radio and music	
AC4-8NSP - Unspecified leisure	
AC9A - Travel except travel related to jobs	Mobility
AC913 - Travel to/from work	Mobility
AC9B - Travel related to study	
AC936 - Travel related to shopping and services	
AC938 - Transporting a child	
AC9C - Travel related to other household purposes	
AC9D - Travel related to leisure, social and associative life	
AC90NSP - Unspecified travel	Mobility
AC99NSP - Unspecified time use	Other

Figure 44 Mapping of categories of time use for Eurostat

Activities such as shopping are classified as “unpaid work”. This shows one side of the challenge of quantification and classification. Shopping can be both for groceries and for clothing, devices, etc. These would belong to two different categories.

Sweden	
Activities	
Gainful employment, etc.	Paid work
Business travel	Mobility
Gainful employment, total	
Housework	
hence Cooking	Unpaid work
Washing, unveiling	Unpaid work
Cleaning of the home	Unpaid work
Washing, ironing	Unpaid work
Maintenance work	Unpaid work
Caring for own children	Unpaid work
hence Supervision and assistance to children	
Help with homework	
Play with children	
Conversations with children	
Reading aloud for children	
Parent meetings etc.	
Attendance at children's active.	
Other child care	
Caring for others	Unpaid work
Purchase of goods and services	Unpaid work
Other homework	Unpaid work
Travel in connection with homework	Mobility
Homework, total	
Personal care	
Meals	
Travel in sb with personal needs	Mobility
Personal needs, total	
Studies	Education
Travel in connection with studies	Mobility
Studies, total	
Sports and outdoor life	Leisure
Association activities etc.	Leisure
Entertainment culture	Leisure
Social gatherings	Leisure
TV and radio	Leisure
Reading	Leisure
Hobbies	Leisure
Other free time	Leisure
Travel in sb with free time	Mobility
Free time, total	
Other, uncodable	Other

Figure 45 Mapping of categories of time use for Eurostat

9.2. Appendix for chapter 5

9.2.1. Economic Job Productivity

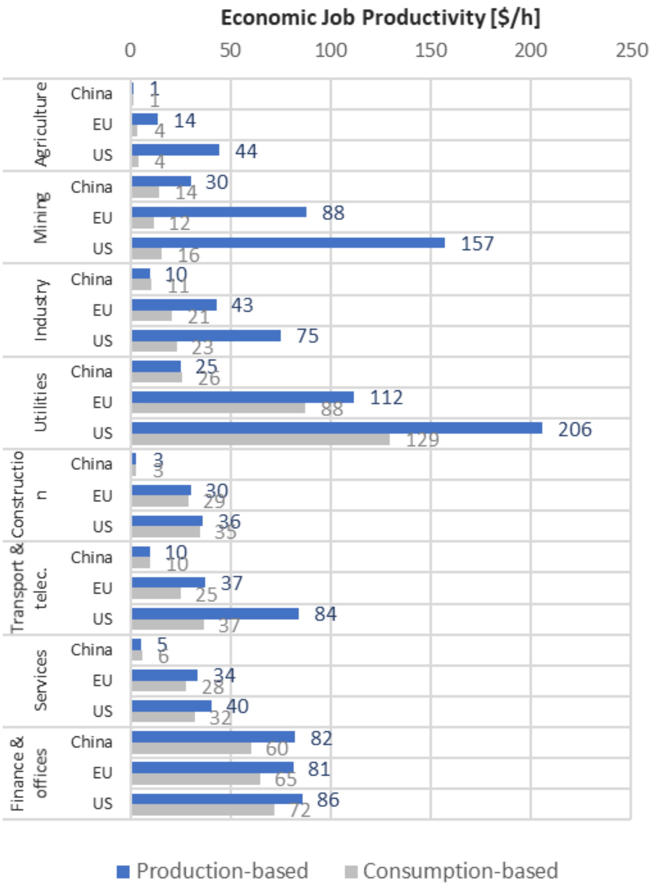

Figure 46 Production and consumption-based Economic Job Productivity (EJP, in $/h) by country and sector

9.2.2. Energy Metabolic Rate

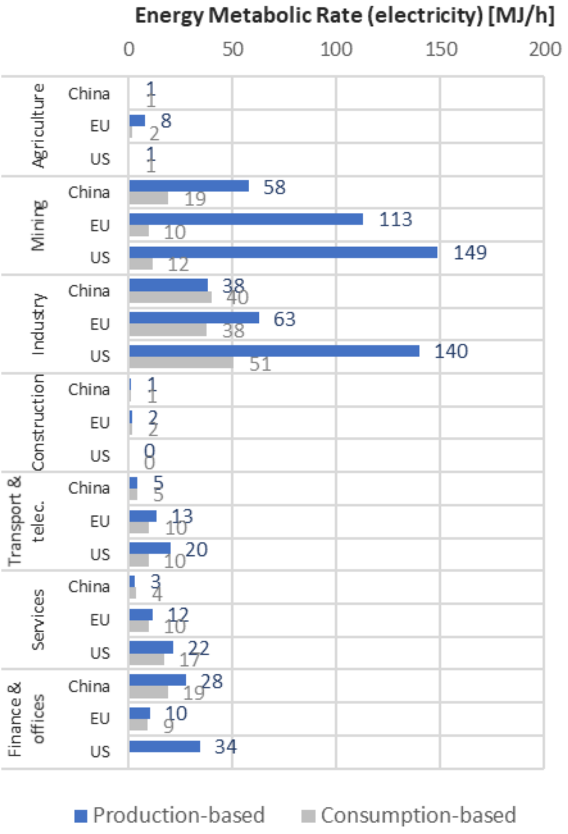

Figure 47 Production and consumption-based Energy Metabolic Rate (EMR, in MJ/h) for electricity by country and sector

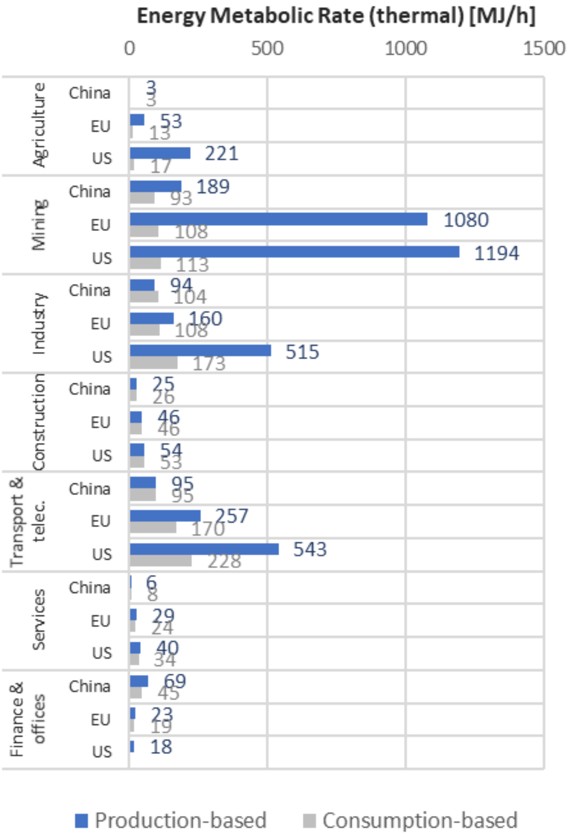

Figure 48 Production and consumption-based Energy Metabolic Rate (EMR, In MJ/h) for thermal energy by country and sector

9.3. Regional and economic classifications

Table 9 Countries used for the calculation and aggregation for the analysis

Countries and regions for calculation	**Regions of analysis**
China	CHN
United States	US
Austria	EU
Belgium	
Czech Republic	
Denmark	
Estonia	
Finland	
France	
Germany	
Greece	
Hungary	
Ireland	
Italy	
Latvia	
Luxembourg	
Netherlands	
Poland	
Portugal	
Slovakia	
Slovenia	
Spain	
Sweden	
Great Britain	
Cyprus	
Lithuania	
Malta	
Romania	
Bulgaria	
Australia	ROW
Canada	
Japan	
Korea	
Mexico	
Norway	
Switzerland	
Turkey	
Brazil	
Croatia	
India	
Indonesia	
Russia	
South Africa	
Taiwan	
Rest of the World	

Table 10 Matching of TIVA and Exiobase economic sectors classifications.

TiVA classification		Exiobase industry classification
C01T05	Agriculture, hunting, forestry and fishing	Cultivation of paddy rice
		Cultivation of wheat
		Cultivation of cereal grains nec
		Cultivation of vegetables, fruit, nuts
		Cultivation of oil seeds
		Cultivation of sugar cane, sugar beet
		Cultivation of plant-based fibers
		Cultivation of crops nec
		Cattle farming
		Pigs farming
		Poultry farming
		Meat animals nec
		Animal products nec
		Raw milk
		Wool, silk-worm cocoons
		Manure treatment (conventional), storage and land application
		Manure treatment (biogas), storage and land application
		Forestry, logging and related service activities (02)
		Fishing, operating of fish hatcheries and fish farms; service activities incidental to fishing (05)
C10T14	Mining and quarrying	Mining of coal and lignite; extraction of peat (10)
		Extraction of natural gas and services related to natural gas extraction, excluding surveying
		Extraction, liquefaction, and regasification of other petroleum and gaseous materials
		Mining of uranium and thorium ores (12)
		Mining of iron ores
		Mining of copper ores and concentrates
		Mining of nickel ores and concentrates
		Mining of aluminium ores and concentrates
		Mining of precious metal ores and concentrates
		Mining of lead, zinc and tin ores and concentrates
		Mining of other non-ferrous metal ores and concentrates
		Quarrying of stone
		Quarrying of sand and clay
		Mining of chemical and fertilizer minerals, production of salt, other mining and quarrying n.e.c.
C15T16	Food products, beverages and tobacco	Processing of meat cattle
		Processing of meat pigs
		Processing of meat poultry
		Production meat products nec
		Processing vegetable oils and fats
		Processing of dairy products
		Processed rice
		Sugar refining
		Processing of Food products nec
		Manufacture of beverages
		Manufacture of fish products
		Manufacture of tobacco products (16)
		Manufacture of textiles (17)

C17T19	Textiles, textile products, leather and footwear	Manufacture of wearing apparel; dressing and dyeing of fur (18) Tanning and dressing of leather; manufacture of luggage, handbags, saddlery, harness and footwear (19)
C20	Wood and products of wood and cork	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials Re-processing of secondary wood material into new wood material
C21T22	Pulp, paper, paper products, printing and publishing	Pulp Re-processing of secondary paper into new pulp Paper Publishing, printing and reproduction of recorded media (22)
C23	Coke, refined petroleum products and nuclear fuel	Manufacture of coke oven products
		Petroleum Refinery
		Processing of nuclear fuel
C24	Chemicals and chemical products	Plastics, basic Re-processing of secondary plastic into new plastic N-fertiliser P- and other fertiliser Chemicals nec
C25	Rubber and plastics products	Manufacture of rubber and plastic products (25)
C26	Other non-metallic mineral products	Manufacture of glass and glass products Re-processing of secondary glass into new glass Manufacture of ceramic goods Manufacture of bricks, tiles and construction products, in baked clay Manufacture of cement, lime and plaster Re-processing of ash into clinker Manufacture of other non-metallic mineral products n.e.c.
C27	Basic metals	Manufacture of basic iron and steel and of ferro-alloys and first products thereof Re-processing of secondary steel into new steel Precious metals production Re-processing of secondary preciuos metals into new preciuos metals Aluminium production Re-processing of secondary aluminium into new aluminium Lead, zinc and tin production Re-processing of secondary lead into new lead, zinc and tin Copper production Re-processing of secondary copper into new copper Other non-ferrous metal production Re-processing of secondary other non-ferrous metals into new other non-ferrous metals Casting of metals
C28	Fabricated metal products	Manufacture of fabricated metal products, except machinery and equipment (28)
C29	Machinery and equipment n.e.c.	Manufacture of machinery and equipment n.e.c. (29)
C30T33X	Computer, electronic and optical equipment	Manufacture of office machinery and computers (30)
C31	Electrical machinery and apparatus, nec.	Manufacture of electrical machinery and apparatus n.e.c. (31)
C30T33X	Computer, electronic and optical equipment	Manufacture of radio, television and communication equipment and apparatus (32) Manufacture of medical, precision and optical instruments, watches and clocks (33)
C34	Motor vehicles, trailers and semi-trailers	Manufacture of motor vehicles, trailers and semi-trailers (34)
C35	Other transport equipment	Manufacture of other transport equipment (35)
	Manufacturing nec; recycling	Manufacture of furniture; manufacturing n.e.c. (36)

C36T37		Recycling of waste and scrap Recycling of bottles by direct reuse
C40T41	Electricity, gas and water supply	Production of electricity by coal Production of electricity by gas Production of electricity by nuclear Production of electricity by hydro Production of electricity by wind Production of electricity by petroleum and other oil derivatives Production of electricity by biomass and waste Production of electricity by solar photovoltaic Production of electricity by solar thermal Production of electricity by tide, wave, ocean Production of electricity by Geothermal Production of electricity nec Transmission of electricity Distribution and trade of electricity Manufacture of gas; distribution of gaseous fuels through mains Steam and hot water supply Collection, purification and distribution of water (41)
C45	Construction	Construction (45)
C50T52	Wholesale and retail trade; repairs	Re-processing of secondary construction material into aggregates Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motor cycles parts and accessoiries Retail sale of automotive fuel Wholesale trade and commission trade, except of motor vehicles and motorcycles (51) Retail trade, except of motor vehicles and motorcycles; repair of personal and household goods (52)
C55	Hotels and restaurants	Hotels and restaurants (55)
C60T63	Transport and storage	Transport via railways Other land transport Transport via pipelines Sea and coastal water transport Inland water transport Air transport (62) Supporting and auxiliary transport activities; activities of travel agencies (63)
C64	Post and telecommunications	Post and telecommunications (64)
C65T67	Financial intermediation	Financial intermediation, except insurance and pension funding (65) Insurance and pension funding, except compulsory social security (66) Activities auxiliary to financial intermediation (67)
C70	Real estate activities	Real estate activities (70)
C71	Renting of machinery and equipment	Renting of machinery and equipment without operator and of personal and household goods (71)
C72	Computer and related activities	Computer and related activities (72)
C73T74	R&D and other business activities	Research and development (73) Other business activities (74)
C75	Public admin. And defence; compulsory social security	Public administration and defence; compulsory social security (75)
C80	Education	Education (80)
C85	Health and social work	Health and social work (85)
C90T93		Incineration of waste: Food

	Other community, social and personal services	Incineration of waste: Paper Incineration of waste: Plastic Incineration of waste: Metals and Inert materials Incineration of waste: Textiles Incineration of waste: Wood Incineration of waste: Oil/Hazardous waste Biogasification of food waste, incl. land application Biogasification of paper, incl. land application Biogasification of sewage slugde, incl. land application Composting of food waste, incl. land application Composting of paper and wood, incl. land application Waste water treatment, food Waste water treatment, other Landfill of waste: Food Landfill of waste: Paper Landfill of waste: Plastic Landfill of waste: Inert/metal/hazardous Landfill of waste: Textiles Landfill of waste: Wood Activities of membership organisation n.e.c. (91) Recreational, cultural and sporting activities (92) Other service activities (93)
C95	Private households with employed persons	Private households with employed persons (95)
		Extra-territorial organizations and bodies

Table 11 Reference of final economic classification of analysis and classification of calculation

Final	Calculation	
Agriculture	C01T05	Agriculture, hunting, forestry and fishing
Mining	C10T14	Mining and quarrying
Industry	C15T16	Food products, beverages and tobacco
	C17T19	Textiles, textile products, leather and footwear
	C20	Wood and products of wood and cork
	C21T22	Pulp, paper, paper products, printing and publishing
	C23	Coke, refined petroleum products and nuclear fuel
	C24	Chemicals and chemical products
	C25	Rubber and plastics products
	C26	Other non-metallic mineral products
	27	Basic metals
	C28	Fabricated metal products
	C29	Machinery and equipment, nec
	C30T33X	Computer, Electronic and optical equipment
	C31	Electrical machinery and apparatus, nec
	C34	Motor vehicles, trailers and semi-trailers
	C35	Other transport equipment
	C36T37	Manufacturing nec
Utilities	C40T41	Electricity, gas and water supply
Construction	C45	Construction
Services	C50T52	Wholesale and retail trade
	C55	Hotels and restaurants
Transport and telecom	C60T63	Transport and storage
	C64	Post and telecommunications
Finance and offices	C65T67	Financial intermediation
	C70	Real estate activities
	C71	Renting of machinery and equipment
	C72	Computer and related activities
	C73T74	R&D and other business activities
Services	C75	Public admin. and defence
	C80	Education
	C85	Health and social work
	C90T93	Other community, social and personal services
	C95	Private households with employed persons

9.4. Appendix for chapter 6

9.4.1. Methods - matching National Accounts and SBS data

Human Activity data in hours of work was not available for all countries and years. In some cases, there was data on the number of workers. In this case, the hours per worker of Transport equipment or Manufacturing, if existent, was used as a proxy to calculate working hours via number of workers.

For data in levels lower than C29 (C291. C292 and C293), a different database to National Accounts was required. This includes value added, number of workers, and hours worked. However, these databases do not match at the level C29 for workers and hours worked. The comparison between National Accounts and SBS databases for number of workers can be found in Figure 49. There is a disagreement between databases that range from a small percentage to even 50% more or even doubling (e.g., France). In the case of value added, the units are different (value added at factor cost and gross value added), but the ratios EJPs and PPR also give scenarios inconsistent with those in the level C29 with the national accounts.

Eurostat recommends not using different databases with the same variables due to the methodological differences (statistical unit). Also, it warns that the values are more likely to be not comparable when there is the risk of loss of confidentiality. This happens when there is a small number of companies, usually in small countries. However, the problem of disagreement was bigger in France and Poland, two of the largest countries. SBS is based on surveys, whereas NA is based on survey and administrative data. Of course, a certain level of discrepancy is always expected, but with these large differences, we have given for France. In conversations with INSEE (French statistical office), we were told that the procedures were different for the two databases. This is a further sign as well of the possibility of not considering the same functions in all countries even though we are analysing a single NACE division. Such discrepancies are also related to the uneven allocation of resources for each database, and the one-to-many mapping of an economic unit to a diversity of NACE categories. There are joint productions, or even manufacturing of different products, design and other activities within the same company or building. NACE follows a top-down approach, which “follows a hierarchical principle: the classification of a unit at the lowest level of the classification must be consistent with the classification of the unit at the higher levels of the structure.” (Eurostat, 2008, p. 28).

To manage this situation and ensure the match, we have used the Gross Value Added and Human Activity from National Accounts at level C29 and the shares of the subsectors from SBS for the figures in section 6.3.4.

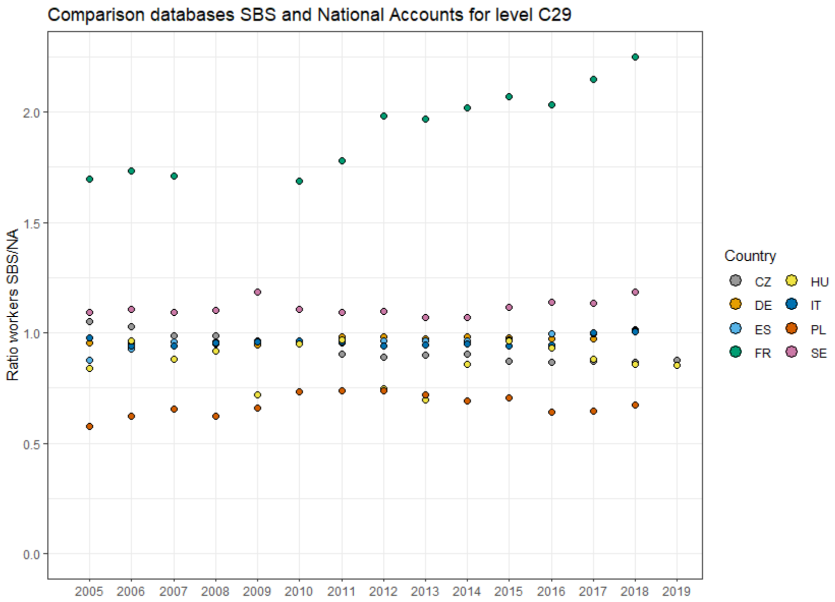

Figure 49 Comparison of SBS and National accounts databases for number of workers

9.4.2. Vehicle production

The focal sector of analysis produces motor vehicles, a final product, and their specific intermediate parts. The diversity of vehicles in terms of function and size also makes it difficult to assess the output (different kinds of passenger cars, buses, heavy trucks, LCVs, etc.). This is a product mix problem, with a large diversity of processes and intermediate and final products both at the division and group levels. The final production of vehicles must be considered only as a rough proxy of the level of specialization of each country in the final production of vehicles. Moreover, vehicle manufacturers can also devote themselves to services such as insurance and financialization (do Carmo et al., 2019). This makes it challenging to allocate the companies in the national accounts' classification.

Figure 50 shows the production of the four main types of vehicles in the EU8 countries in 2015. The number of passenger cars is a higher order of magnitude compared to LCVs, heavy trucks, and buses. The country that produced more passenger cars and heavy trucks was Germany (4.9M and 0.18M, respectively) at a considerable distance from the rest. Moreover, for LCVs, it was the third largest producer (367k), and for buses, the 2nd (6k), at a very close distance from the first, Sweden (6.3k, 1% of its vehicle production). Spain built the largest number of LCVs (0,63M, 22% of its vehicle production).

In all countries, cars are the bulk of production, but the vehicle mix is different. On the EU-8 average, cars represented 82% of the produced vehicles, LCVs were the second with 15%, heavy trucks third with 3%; finally, buses were only 0.2% of the four types. The country with the lowest share of passenger cars was Poland (56%), primarily due to a relatively large production of LCVs (40%). Conversely, Hungary and Czechia manufactured almost only passenger cars (more than 99%).

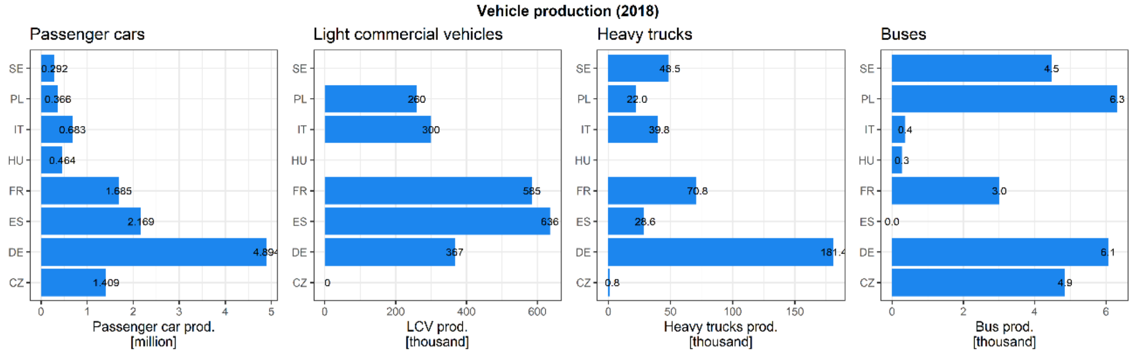

Figure 50 Production of passenger cars, buses, heavy trucks, and light commercial vehicles in the analyzed countries in 2015 (European Automobile Manufacturers Association, 2019)

Vehicles are not only needed for internal supply but they also are a key export item in developed countries to leverage international trade balances. The EU industry has a relatively higher value added than the rest of the world, representing a relatively high share of its exports (Pérez-Sánchez et al., 2021). Figure 51 shows how the production of passenger cars compares to the renovation of the domestic fleet in 2015. The EU-8 balance of production and demand is positive: more cars are manufactured than registered. More than 20% of the production is exported (at least 8 cars per 1000 inhabitants). Four countries have a positive car trade balance regarding the number of cars. This balance in the number of cars can change and even be larger if we account for the value of cars.

Paradoxically, Czechia had at the same time the largest car production per capita (115 cars per 1000 inhabitants) and the fewest registrations (22 cars per 1000 inhabitants). For context, ownership was 485 per 1000 inhabitants (Eurostat, 2021d). Car production in Czechia was more than five times larger than new registrations, confirming that cars are an important export item for that country. Other countries with large production/registration ratios are Hungary (2.6 times larger) and Spain (2 times larger). Germany is the fourth EU8 country with largest production per capita (68 veh/1000 inh.) in relation to new registrations (39 veh/1000 inh.), with only a 1.7 production/registrations ratio. This surplus occurs despite having the largest consumption per capita of the EU8. These German imports and exports are qualitatively different: Germany produces a larger share of higher-end cars (Chiappini, 2012), whereas the ones it imports tend to be in lower segments.

On the other side, there are countries with larger consumption than production: France, Italy, Poland, and Sweden. Sweden has the second-largest number of new registrations per capita (37 cars/1000 inh.), 1.9 times larger than production. We find the largest unbalances in Italy and Poland, with a demand for new cars 2,4 times larger than their production and the lowest car production per 1000 inhabitants of the EU-8 (11 and 12 cars/1000inh, respectively).

The trade of used cars from other European countries can also play a relevant role in the maintenance and growth of vehicle fleets. For example, in 2009, Poland imported more than 425 thousand used cars from Germany (Mehlhart et al., 2011), about half of the new registrations. In Czechia in 2008, the number of new registrations and imported used cars was similar (slightly over 140 thousand vehicles) (Mehlhart et al., 2011).

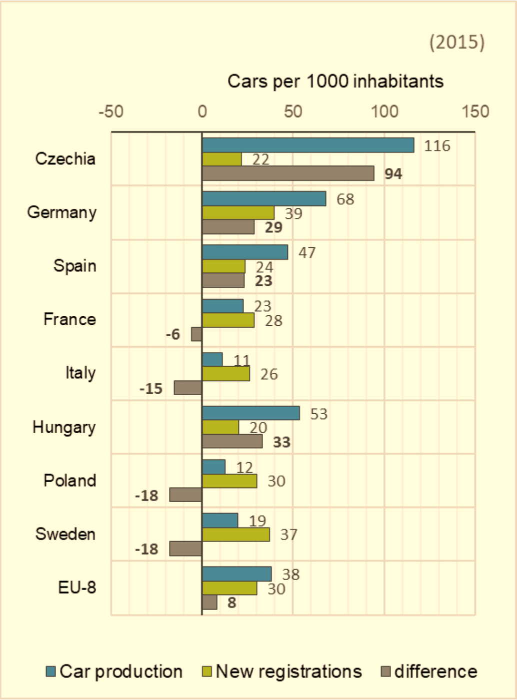

Figure 51 Production and new registrations of passenger cars per 1000 inhabitants by country (2015)

10. Curriculum Vitae

Education:

October 2018 - present	Ph.D. Environmental science and technology *Institut de Ciència i Tecnologia Ambientals (Universitat Autònoma de Barcelona)* Ecological economics and industrial ecology. Thesis title: Studies in societat metabolism – from households to the global economy. Supervisors: Mario Giampietro and Raúl Velasco-Fernández
2016-2017	Master in Interdisciplinary studies in environmental, economic and social sustainability (Industrial and urban ecology) *Institut de Ciència i Tecnologia Ambientals (Universitat Autònoma de Barcelona)* Thesis title: Energy performance at city level: the societal metabolism of Barcelona. Supervisors: Maddalena Ripa and Mario Giampietro
2008-2014	Industrial engineering, mechanical specialization *Escola Tècnica Superior d'Enginyeria Industrial de Barcelona (Universitat Politècnica de Catalunya)* Erasmus: Politecnico di Torino (September 2013- July 2014) Thesis title: Aerodynamic verification and optimization of a model of a small floating offshore wind turbine. Supervisor: Giuliana Mattiazzo
2007-2008	Architecture *Escola Tècnica Superior d'Arquitectura de Barcelona*

Research experience:

November 2017 – present	Predoctoral researcher *Institut de Ciència i Tecnologia Ambientals (Universitat Autònoma de Barcelona)* "Sweden 2050" project for the Swedish Environmental Protection Agency exploring possibilities of sustainable futures for Sweden. Previously on EUFORIE (h2020), IANEX, and MAGIC-Nexus (h2020). Studies on energy metabolism in cities, water metabolism of fracking in the US and embodied resources in trade between China and the European Union.

February - May 2022	Research stay *Leiden University (the Netherlands)* Research stay with Paul Behrens and Tomer Fishman on the integrated product flow analysis of private mobility and residential buildings.

Publications:

Pérez-Sánchez, L.À., Velasco-Fernández, R., Giampietro, M., (2022). Factors and actions for the sustainability of the residential sector. The nexus of energy, materials, space, and time use. *Renew. Sustain. Energy Rev*. 161, 112388. https://doi.org/10.1016/j.rser.2022.112388

Manfroni, M., Velasco-Fernández, R., Pérez-Sánchez, L., Bukkens, S.G.F, Giampietro, M. (2021) The profile of time allocation in the metabolic pattern of society: An internal biophysical limit to economic growth. *Ecological Economics* 190, 107183, https://doi.org/10.1016/j.ecolecon.2021.107183

Pérez-Sánchez, L., Velasco-Fernández, R., Giampietro, M. (2021) The international division of labor and embodied working time in trade for the US, the EU, and China. *Ecological Economics*, 180, https://doi.org/10.1016/j.ecolecon.2020.106909

Velasco-Fernández, R., Pérez-Sánchez, L., Giampietro, M. (2020) A becoming China and the assisted maturity of the EU: Assessing the factors determining their energy metabolic patterns. *Energy Strategy Reviews*, 32, 100562, https://doi.org/10.1016/j.esr.2020.100562

Pérez-Sánchez, L., Giampietro, M., Velasco-Fernández, R., & Ripa, M. (2019). Characterizing the metabolic pattern of urban systems using MuSIASEM: The case of Barcelona. *Energy Policy*, 124, 13-22, https://doi.org/10.1016/j.enpol.2018.09.028

Submitted/under review:

Pérez-Sánchez, L.À., Velasco-Fernández, R., Giampietro, M. Energy metabolism of the automotive industry in European Union countries – implications of functional specialisation in biophysical performance.

Pérez-Sánchez, L.À., Fishman, T., Behrens, P. Undoing the lock-in of suburban sprawl: novel integrated modelling of materials and emissions in urban transformation for decreasing car dependency.

Pérez-Sánchez, L.À., Aguilar-Hernández, G. “Made in Germany”? Social and carbon impacts of the global value chains of final demand and production of the Motor vehicles industry.

Di Felice, L.J., Pérez-Sánchez, L.À., Manfroni, M., Giampietro, M. Energy systems across scales: an embodied nexus perspective.

Conferences:

- 14th Conference of the European Society for Ecological Economics 2022 (Pisa), oral presentation: “Complications of metabolic patterns in a globalized world: The externalization matrix”

- ISIE Socioeconomic Metabolism perpetual online conference. Session 11: Advancing the built environment toward energy and circularity transitions: challenges and opportunities. Oral presentation “Can we balance the GHG emissions and material impacts of densification of suburban sprawl vs. decreasing car dependency?”
- ICTA symposium 2021. Oral presentation: “Sustainability of the residential sector: beyond energy efficiency labelling”
- 43rd International Association for Time Use Research Conference 2021(Barcelona), poster: “Externalization of working time and energy. The EU, China and the US in the international division of labor (2011)”
- Post-Normal Science symposium 2020, oral presentation in a special session on “Uncomfortable knowledge”
- Energy Modelling Platform for Europe 2020, poster: ‘Visions of sustainability for Sweden 2050’
- ICTA-UAB International Conference on Low-Carbon Lifestyle Changes 2020, ICTA-UAB, poster: ‘Effects of the international division of labor on lifestyles – embodied working time in trade for the US, the EU and China’
- European Roundtable for Sustainable Consumption and Production 2019, UPC Barcelona, oral presentation: ‘Working Time and Energy Consumption in Global Production Networks: The Roles of the EU, China and USA’
- Sustainable Urban Energy Systems Conference 2018, TU Delft, oral presentation: ‘Characterizing the energy metabolic pattern of urban systems with MuSIASEM: the case of Barcelona’
- ResNexus 2018, Wageningen University, oral presentation: ‘The Urban Resource Nexus: The end-use matrix as a tool to evaluate urban metabolism in a globalized world’
- ICTA spring symposium 2018, oral presentation: ‘What are the boundaries of the city? The case study of Barcelona’

Summer school teaching

Complex sustainability challenges: the nexus between water, energy and food – (LIPHE4 association) 8-12 July 2019 – Bellaterra, Spain

Can cities be sustainable? Novel tools to explore urban metabolism. Co-host: ENVIROSPACE Lab, University of Geneva- 2-6 July 2018 – Geneva, Switzerland

Summer school attendance:

A critical appraisal of current narratives of sustainability through quantitative storytelling – Liphe4 association – Department of biology, University of Naples Federico II – 26-30 July 2017 - Naples, Italy

LOCOMOTION summer school – University of Zagreb, Universidad de Valladolid, etc. - 4 – 15 September 2022 - Dubrovnik, Croatia

Other Ph.D. activities

Manager of the Coursera online course “Sustainability of social-ecological Systems: the nexus between water, energy and food”

Grants and fellowships:

Grants for the recruitment of new research staff - FI PhD grant – Government of Catalonia (grant number 2019FI_B01317)