Adequate service provision as the guide for energy transitions and international development

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This thesis is dedicated to my parents Alejandra and Carlos and my twin sister Katia whose efforts and sacrifices have helped to get me to this point in my life.
This thesis is also dedicated to my uncle Charles Oden, who was so proud of me for being in Cambridge and planned to visit for graduation, but sadly passed away from COVID-19 complications in February 2021.

Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements. This dissertation contains fewer than 65,000 words including appendices, bibliography, footnotes, tables and equations and has fewer than 150 figures.

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Abstract

The reliance of human societies on fossil-fuelled energy supply used for human activities has increased greenhouse gas (GHG) emissions to levels that cause unprecedented atmospheric warming. The emissions have been the result of a handful of countries that industrialised, changing their systems and improving the well-being of their population over time. Given the global harmful consequences of such emissions, industrialised economies have planned an energy transition to curb them. In contrast, many developing countries that need higher levels of well-being have agreed to emission-limiting international agreements, forcing them to seek alternative ways to increase well-being.

GHG emissions are connected to resource consumption (i.e. energy and materials), which in turn provide the ‘services’, either to cover needs or desires by people. The delivery of services requires multiple resource transformations, with inefficiencies at each transformation. Developing countries face the challenge to deliver services and increase well-being, while limiting emissions. This thesis refers to this idea as climate-compatible development.

Researchers have explored the links between energy use, development and well-being, but have mostly overlooked the multiple transformations and losses that occur between resource extraction and service provision. Such in-depth exploration is hindered by a lack of granular data describing these resource transformations. As a result, technical and policy efforts to reduce emissions focus mainly on low-carbon energy supply options, despite the high emission reduction potential from end-uses, which are closer to services. This thesis postulates that service provision is more closely linked to development outcomes, than primary energy supply. Therefore, assessing historical service provision, will elucidate ways to deliver decent well-being levels with reduced emissions.

The research is organised into three main areas. The first attempts to measure to what extent increases in service delivery have led to higher levels of development, using indicators at several transformation stages for the first time. The research tracks variations in 34 resource transformation and development indicators over time, across 100 countries. Regressions between these indicators suggest that for constant service-related levels, development is decoupling from the service indicators with significant regression results. The links between the pairs of indicators depend on the service studied, the model used, the indicators in question, the countries included and specific temporal dynamics. The pace of change of service provision is affected by dynamics that require systematic understanding.

The second research area explores the use of scarce developing country data to investigate service provision. A bottom-up analysis and stakeholder interviews are undertaken to investigate which insights around service provision may be drawn from analysing national household surveys in Uganda. Changes in energy sources and energy use patterns are examined from 2009 to 2016 focusing on lighting and cooking, aggregated by urban and rural settlements, and household expenditure deciles. Transformations of final to useful energy are evaluated for cooking, including an uncertainty analysis. The results reveal a slow transition away from traditional biomass and kerosene use, especially for lighting in low-expenditure rural settlements and cooking in general. Fuel stacking, mainly for cooking, is contributing to the slow transition and to higher emissions, especially in wealthier households. Changes in service provision are occurring in the country, related to lighting, transport, and mobile phones, yet the changes face local challenges such as language diversity.

The third research area explores which stages of resource transformation (i.e. primary, final, useful energy and services) are represented in policy and regulations. A country-level database of 10,811 policies for the period 1960-2020 is analysed. Several machine learning models to predict the policy characteristics (i.e. instrument type, topic) and scope (i.e. sector, end-use, technology) are created. The highest prediction accuracy resulted to be 80%, depending on the number of labels to predict. The evaluation of policy mixes using the predicted values suggests that most economic sectors have a mix of well-balanced policies after 2005. The analysis revealed there has been a shift in the past two decades away from similar proportions of Buildings, Transport and Generation policies between 2000 and 2009 to a focus on Buildings, and some Transport in the next decade. The results also suggest that regulating activities closer to services is increasing the number of policies required. Low-income countries focus mainly on energy generation policies, yet Sub-Saharan Africa is beginning to regulate later stages of the chain, e.g. final, through Buildings policies.

The fundamental contributions of this thesis to the literature are the confirmation of links and interacting factors between service delivery and development outcomes, including the identification of suitable indicators for evaluating service provision. Further, the use of country-level surveys is shown to identify levels and uncertainty of household service delivery in developing countries, with useful stakeholder insights. Finally, the resource transformation stages included in policies are shown to have changed over time towards higher service coverage, but less so for low-income countries.

Publications, Conferences and Grants

Material in this thesis has been submitted to journals and presented at conferences as shown below.

Journal papers:

- Cervantes Barron, K., Diaz Anadon, L., Cullen, J.M., *Measuring energy service provision in developing countries*, World Development (Preparing for resubmission)
- Cervantes Barron, K., Cullen, J.M., *Developmental and environmental implications of global energy services*, Resources, Conservation and Recycling (Preparing for resubmission)

Conference Presentations and Special Session Organisation:

- Poster:*"Exploring the link between energy services and development"*, Cambridge University Fluids, Energy and Turbomachinery Expo (FETE) Conference, 20th July 2017, Duxford, UK
- Presentation and special session co-organisation: *"Exploring the link between energy services and human development"*, in the special session *"Human development and linkages to energy services"*, 12th International Conference of the European Society for Ecological Economics (ESEE) 20-23 June 2017, Budapest, Hungary
- Presentation and co-creation parallel session co-organisation and co-chairing: *"Human Well-Being: Linking useful exergy to human well-being and development"*, International Exergy Economics Workshop (IEEW) 13-15 May 2018, Lisbon, Portugal
- Presentation: *"Enlightening the Implications of Device Innovation and Efficiency for Energy Use"*, 1st International Sustainable Production and Consumption Conference (ISPCC) 4-5 October 2018, Manchester, United Kingdom
- Presentation and special session co-organisation: *"Ugandan energy use at household level"* in the special session *"International contexts of energy use: how much and what for?"*, 13th International Conference of the European Society for Ecological Economics (ESEE) 18-21 June 2019, Turku, Finalnd

Also contributor to the analysis for Chapter 2 in:

- Global Electric Vehicle Outlook, International Energy Agency (2019)

Additional research grant awarded:

- Recipients: Cervantes Barron, K., Diaz Anadon, L., Cullen, J.M., *The role of Chinese manufacturing in the selection of technologies and devices related to energy services brought to developing-country projects*, In Search of Good Energy Policy Small Grants Scheme, Isaac Newton Trust/ Energy Policy Research Group (EPRG) (2018)

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Nomenclature

Organisations

EU	European Union
EUROSTAT	European Statistics
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
OECD	Organisation for Economic Co-operation and Development
UK	United Kingdom
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change

Others

CCS	Carbon Capture and Storage
DLS	Decent Living Standards
EUETS	EU Emission Trading Scheme
GHG	Greenhouse gases
GHG	Greenhouse-gas emissions
GIS	Geographic Information Systems
GTAP	Global Trade Analysis Project
IAM	Integrated Assessment Model

kNN	K Nearest Neighbours
LEAP	Long-range Energy Alternatives Planning System
LSMS	Living Standards Measurement Surveys
MDG	Millennium Development Goals
MEPS	Minimum Energy Performance Standards
NDC	Nationally Determined Contributions
NLP	Natural Language Processing
NPS	National Panel Survey
OLS	Ordinary-Least Square
PV	Photo-voltaic
R&D	Research and Development
RD & D	Research, Development and Distribution
SCC	Social Cost of Carbon
SDG	Sustainable Development Goals

Variables

CO_2	Carbon dioxide
AFR	Sub-Saharan Africa
CPA	Centrally planned Asia and China
EEU	Central and Eastern Europe
FSU	Former Soviet Union
GDI	Gender Development Index
GDP	Gross Domestic Product
GDP	Gross Domestic Product
GII	Gender Inequality Index

GINI	Gini index
GLOB	International country coverage
GNI	Gross National Income
HDI	Human Development Index
HIC	High Income Countries
IHDI	Inequality-adjusted Human Development Index
LAC	Latin America and the Caribbean
LIC	Low Income Countries
LMC	Lower Middle Income Countries
MEA	Middle East and North Africa
MPI	Multi-dimensional Poverty Index
NAM	North America
PAO	Pacific OECD
PAS	Other Pacific Asia
SAS	South Asia
SPI	Social Progress Index
UMC	Upper Middle Income Countries
WEU	Western Europe

1

Introduction

1.1 Resources and climate change

The story of the universe is one of energy transformations. On Earth, biogeochemical cycles were formed which used the Sun's energy to produce reactions that eventually supported life. Much later, after homo sapiens had developed key skills, humans populated much of the Earth, using and modifying the resources available to satisfy their needs and support their activities. Since the Sun was the main source of energy and was converted into phytomass via photosynthesis, the amount of energy available and the time to replenish it was constrained, making traditional human societies reliant on "instantaneous (or minimally delayed) and constantly replenished solar income" (Smil, 2017). Eventually, humans learned to harness other resources on Earth and harness and transform some of the available types of energy. From all the available Earth's resources, only those that could produce some benefit for human activities were used. That included thermal energy of steam to move turbines, potential energy in dams and chemical energy from Carbon-Hydrogen bonds. Humans also learned to use movers to increase their pace and capacity to transport objects. These movers were other living beings at first, but later other resource transformations to power and creating structures for the new movers were involved (Smil, 2017).

The population grew alongside social complexity with the different configurations of resources used and systems in place. As societies grouped and conquered land and later formed countries, securing resource supply to facilitate human activities became of national interest. The resource accessibility and distribution among different nations, as well as ways to harness them, have been shaping the relationships between nations and the power one may hold over another (Global Commission on the Geopolictics of Energy Transformation and IRENA, 2019).

Given the marked long-lasting effect of humans on Earth, academics conceded that a new term to define the effects as a geological epoch was necessary (Steffen et al., 2011). The term Anthropocene was then defined by Lewis and Maslin (2015) suggesting two possible years for it to be counted from: 1610 and 1964. For both of these years, the introduction of defining human activities created a deep shift in the way human society functioned, leading to anomalies in global temperatures. In 1610 the interaction between Europeans and Americans post 1492 led to a homogenisation of distinct biotas, including crops being grown in non-native places, and global trade (Lewis and Maslin, 2015). In turn, in 1964 with the influence of human activity including the use of materials such as petrochemicals, cement, other minerals and compounds, as well as nuclear bomb testing led to a jump of carbon in 1964, as shown by the dated annual rings of a pine tree in Poland (Lewis and Maslin, 2015). Regardless of the year chosen as the start, the Anthropocene is influenced by the harnessing of fossilised remains for energy supply, whose widespread use began in the Industrial Revolution, even if no geological starting point may be identified during it (Lewis and Maslin, 2015). The coal-fired steam engine developed by James Watt and commercialised in the 18th century brought an over two-century-long age where fossilised remains (coal, oil and gas) were the main energy sources harnessed and had a seemingly limitless reserve of energy. This would have been good news for the world if not for the carbon dioxide (CO_2) that is released into the atmosphere when fossil fuels are combusted. A quantum physical property of CO_2 is absorbing electromagnetic radiation at infrared wavelengths (Howard et al., 1956). When infrared radiation is trapped with atmospheric CO_2 that would otherwise radiate from Earth to outer space, it produces an atmospheric heating effect. Thus, CO_2 is part of the compounds known as a greenhouse gases (GHG). If small CO_2 quantities were emitted, there would not be a problem, however the amount of fossil fuels used has led to an accelerated increase in atmospheric heating that threatens many life forms on Earth (Warren et al., 2018) and the stability necessary for human societies. Other challenges have arisen along CO_2 accumulation such as the accumulation of other GHG e.g. methane, increased pollution, deforestation and biodiversity losses (World Bank, 2020*d*).

The consequences produced by the extensive use of fossil fuels are forcing countries to find alternative systems to replace the ones they have locked themselves into. The establishment of such alternative systems is known as the *energy transition*, where alternative energy sources and practices should limit the impact of climate change. The success of the energy transition will broadly determine the extent to which climate change impacts will persist, e.g. the displacement of considerable amounts of people, especially given some are already occurring in the form of severe weather effects (Jolly et al., 2015; Cai et al., 2017; Moore et al., 2017). Barriers to changing the fossil-fuel-dependant systems are the unequal geographical resource distribution and wealth that is still derived from such fuels, as well as the costs associated with changing systems.

Achieving net zero emissions targets in time will require large-scale changes to the energy system, deployment of climate mitigation solutions, and the rapid development of new technologies (Hart 2020). Supporting activities include financing, national policy creation to regulate the transitions in an equitable manner, and fostering international cooperation (Diaz Anadon et al., 2011, Chapter 5). All these actions should occur while preserving and enhancing human well-being.

1.2 Services and the misconceptions around them

The systems developed by societies over time have included several resource (i.e. energy and materials) transformations such as the ones shown in figure 1.1, which highlights the main energy transformations and losses, as well as the ancillary devices and systems. The energy flows begin with the use of energy sources (i.e. coal, gas, solar, wind), which comprise what is known as *primary energy*. Primary energy is converted into *final energy*, which corresponds to refined fuels and electricity, where the latter is distributed to systems that use it. Final energy undergoes one more transformation where it becomes *useful energy*, due to the use of devices (e.g. cooking stoves) that deliver desired activities. Finally, the delivery of desired activities or satisfaction of consumer demands is known as *services* (e.g. communication, sustenance, thermal comfort, illumination). Services are delivered using ancillary materials, which were defined by Cullen et al. (2011) as *conversion devices* (e.g. engines, furnaces, lighting devices). Conversion devices transform energy from primary to final. Consumers purchase final energy (i.e. electricity, charcoal, transport fuels), and convert it to useful energy (i.e. the heat, cooling, light, and motion) with the help of *passive systems*, which are the systems which hold or trap useful energy (e.g. the building shell, vehicle body or illuminated area). Ultimately, demand for services drives demand for the previous transformations, and, as it will be argued in this thesis, the provision of services is linked to human well-being.

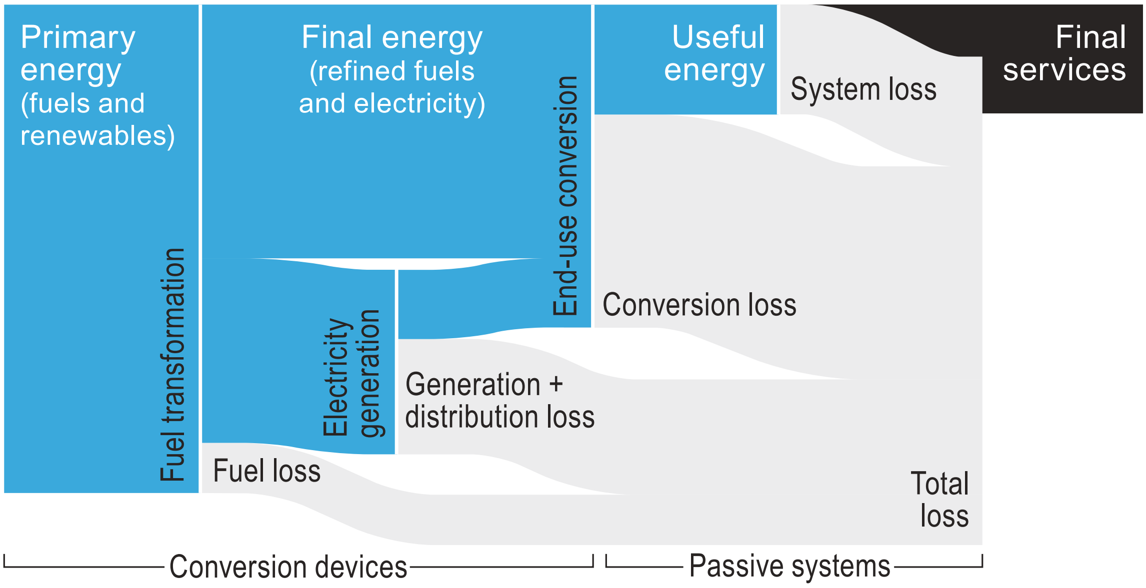

Fig. 1.1 Schematic tracing the flow of energy from primary energy, through final and useful energy to services. Adapted from Cullen and Allwood (2010).

Engineers usually focus on primary or final energy, and very rarely on the useful energy delivered to consumers, in the form of heat, light, motion, and cooling, implicitly assuming that it is what the consumer wants. In fact, it is not the primary, final or even useful energy that are desired, but the service— the thermal comfort, illumination, or sustenance— that is delivered as useful energy is temporarily held or trapped before being lost to the environment. For example, heat is delivered into a home, and the passive system (i.e. the building shell or fabric holds or traps the heat for a period of time, delivering thermal comfort to the occupants). Other passive systems are vehicles which translate the work of the engine to mobility for the passenger, and a building interior which reflects light proving more illumination. The efficiency (or efficacy) with which the passive system is able to trap or hold the useful energy depends on the building insulation, the aerodynamics of the vehicles or the reflectivity of the interior. This efficacy of passive systems varies greatly across different energy pathways and useful energy forms.

Apart from the engineering considerations we have discussed thus far, services will also require certain physical and financial systems to be put in place (Grubler et al., 2012). These systems can enable the end-use devices and passive systems to be bought and operated. These additional systems will not be addressed in this thesis, but should be considered for practical purposes.

The link between energy and societies has been quantified as early as the 1860's, noting that energy plays "a crucial role in the link between societies and their biophysical environments" (Rosa and Keating, 1988). Most countries prioritise the expansion of primary energy supply, including electricity generation and distribution, driven, at least in part, by the desire to increase well-being for the population. However, between primary energy accounts and the final delivery of services, the complex resource chain (as shown in figure 1.1) to convert primary energy and materials into useful forms is required. Furthermore, energy conversion devices operate under specific engineering principles, at varying efficiencies, and in different combinations along parallel energy 'pathways'. Such variances allow for numerous different configurations of devices and corresponding differences in pathway efficiencies. Demand for services also depends on local conditions, such as weather, culture and resource availability, and thus varied system configurations are required- even within a country- if service provision is to be adequate. Thus, primary energy increases are not enough to deliver the same or enough services everywhere. Brand-Correa and Steinberger (2017) also elucidate that diverse energy sources provide different services, so different well-being configurations should be expected.

The most complete historical account of a country's service levels over time found in the literature is the work of Fouquet (2016) about the United Kingdom (UK). Fouquet covered several services, with figure 1.2 showing an example of Fouquet's research using lighting provision. This shows that final energy increased steadily until 1900 and then from 1960 onward, however the delivery of service as lumen-hour per capita did not change. This was because of the inefficiency of conversion devices. Once electricity was used and electric devices became more efficient and widely adopted, service provision increased steadily. The implications of their research are that efforts that are solely focused on increasing primary energy supply can fall short on delivering the services needed.

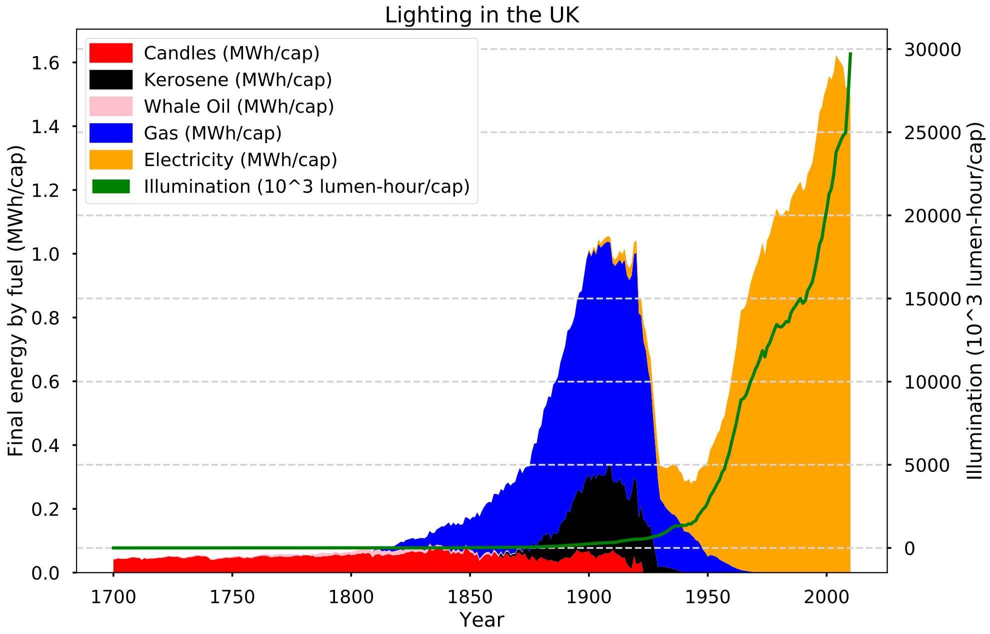

Fig. 1.2 Historic final energy and the service of illumination in the UK. Adapted from (Fouquet, 2014, 2016). Delivered illumination increases over time, while illumination technologies change, thus impacting the energy required to provide the service. Energy used per unit of service delivered is reduced due to higher efficiencies over time.

1.3 Climate-compatible global development

Attempts to define ‘development’ have been made by many academics and development bodies, covering all aspects of economic, social, material and spiritual needs and wants. This section focuses on the non-economic aspects of development in the literature. For example, Todaro and Smith (2012) define ‘development’ as the “movement of a social system from an unsatisfactory condition of life towards achieving their basic material and spiritual needs and aspirations”. Sen (1999) states “development has to be more concerned with enhancing the lives we lead and the freedoms we enjoy”. Concepts of development are closely aligned with sustainability, which is defined by the Brundtland Commission (1987) as meeting “the needs of the present without compromising the ability of future generations to meet their own needs”.

Social transformations over the timespan of centuries have allowed for social configurations where human activities are organised to facilitate prosperity and well-being for some at the expense of others. Dorninger et al. (2021) found that high-income nations imported resources from low-income ones at a cost of monetary trade deficits, thus showing the inequality of global resource exchanges. As global interdependency increases, the formed networks and systems also have higher complexity and become hard to understand and change. So, the fate of one nation finds itself linked to that of the others. According to Keohane and Victor (2016), the changes require deep international cooperation to consider the structure of the problem posed by climate change and national preferences for policy action. A significant challenge is then that changes that need to be put in place relatively quickly to be effective might be delayed and cause much harm to human society.

The detrimental impacts of climate change are suffered in all countries, albeit at different impact levels, despite the drivers of climate change being unequally distributed among countries. Studies of detrimental climate change impacts are increasingly common, e.g. the social cost of carbon (SCC), which showed that the total SCC for agriculture goes from having net benefits to net costs of \$ 8.5 ton^{-1} CO_2 globally as warming increases beyond 2°C (Moore et al., 2017). Other known impacts of climate change are higher food prices, deteriorating health conditions, and exposure to disasters, such as floods (World Bank, 2020*d*). The impacts of climate change are being exacerbated by other phenomena such as the COVID-19 pandemic, with estimations suggesting that an additional 88-115 million people will be pushed into extreme poverty in 2020, with the total rising to as many as 150 million by 2021 (World Bank, 2020*a*), as well as conflicts in some parts of the world, leading to more than 40 percent of the poor living in conflict-affected countries (World Bank, 2020*d*). It then becomes clear that strategic actions to limit the impacts of climate change are needed to regain any progress made in well-being for current and future generations, while addressing poverty and conflict.

Countries at national and international levels have made different agreements to increase development or to limit climate change. Among the most relevant agreements for this thesis are the Millennium Development Goals (MDG), which were a set of goals set in 2000, whose focus included halving extreme poverty rates, and providing universal primary education, all by the target date of 2015 (UN, 2000). As follow-up, in 2015 the Sustainable Development Goals (SDGs) were put in place (UN, 2016). These include goals for 2030 around the topics of poverty, inequality, climate change, environmental degradation, peace and justice. Relevant international climate change agreements have included the Kyoto Protocol and the EU Emission Trading Scheme (EUETS) (EU, 2005), with entered into force and were set up respectively in 2005, and the 2016 Paris Agreement (UNFCCC, 2016). The EUETS encompasses ca 45$\%$ of the EU's GHG emissions. The Paris Agreement included country pledges to limit GHG emissions, which involve setting future emission targets and exploring the necessary actions required to meet them. Committed actions are recorded as

Nationally Determined Contributions (NDC), and are administered by the UNFCC Secretariat (UNFCCC, 2019).

This thesis will offer insights regarding the provision of services that may contribute to emission reductions while advocating for well-being to be at the forefront of changes for countries at different stages of development. The remaining sections of this chapter will clarify the focus of the work including the research questions that will be explored.

1.4 Identifying where to act

The Kaya identity (Kaya, 1990) provides a useful method for decomposing the drivers of energy-related GHG emissions into strategic areas for actions to be taken. The identity is shown in equation 1.1, which decomposes GHG emissions from the energy sector into the drivers of population, emissions intensity (emissions per unit of energy), energy intensity of income (energy per unit of income) and income levels of the population (income per capita). Key to the success of the Kaya identity, is being able to identify where improvements in one area are being undermined by another, e.g. reductions in emissions intensity from increasing the use of renewables might be undermined by increases in a country's population.

$$GHG = \underbrace{Pop}_{\text{population}} \times \underbrace{\frac{GHG}{E}}_{\text{emissions intensity}} \times \underbrace{\frac{E}{I}}_{\text{energy intensity of income}} \times \underbrace{\frac{I}{Pop}}_{\text{population's income level}} \tag{1.1}$$

Where GHG is Greenhouse gases emissions, Pop is population, E is energy, and I is income.

The Kaya identity may be adapted to explore additional interactions e.g. to add the flow of energy and materials as stocks to deliver services (Levi, 2018) or including Gross Domestic Product (GDP) to track progress in reductions in emissions (Peters et al., 2017). The Kaya identity is adapted in this thesis to show strategies that may be followed as developing nations increase their demand for services, while limitations on GHG emissions are put in place. Thus, the resulting adaptation is inspired by Levi (2018), although the terms of embodied and direct energy are added, while material stocks are removed to focus on service delivery. The new identity is shown in equation 1.2.

$$\text{GHG} = \underbrace{\frac{GHG}{E}}_{\text{emissions intensity}} \times \left[\left(\underbrace{\frac{E_{Mat}}{M}}_{\text{materials' intensity}} \times \underbrace{\frac{M}{P}}_{\text{product intensity}} \times \underbrace{\frac{P}{S}}_{\text{service intensity}} \right) + \left(\underbrace{\frac{E_{Direct}}{S}}_{\text{direct energy intensity}} \right) \right] \times \underbrace{S}_{\text{service demand}} \tag{1.2}$$

Where GHG is the same as equation 1.1, S is service, E is energy and it is also shown as E_{Mat} and E_{Direct} which refer to energy embodied in materials and direct energy consumption, M is materials and P is the stock of products formed. All the terms must pertain to the same temporal and geographical boundaries. A reduction in any of the terms in equation 1.1 will also lead to a reduction in emissions.

If, as countries develop, more people are to reach sufficient levels of service provision, any or all of the intensity terms in equation 1.2 need to be reduced to not increase emissions. Thus, strategies for each intensity term may be devised. For instance, primary energy interventions could include building low-carbon electricity grid. Final to useful energy interventions are to improve the efficiencies of devices to reduce energy use and emissions (Paoli and Cullen, 2020). Material interventions can be to increase material efficiency in production processes. Finally, service-intensity interventions can include changing habits of energy use e.g. the scenario by Grubler et al. (2018) who find that it is possible to deliver a 1.5°C scenario of global warming using only demand-side options.

Resource efficiency can be used as a term to encompass all intensity reduction options in the adapted Kaya identity. Resource efficiency aims to maximise outputs while reducing inputs. Those outputs may be in physical terms (e.g. number of units produced, customers served), while the inputs may be in physical (energy, feedstocks, labour needed) or economical forms (costs). Resource efficiency is then a useful strategy for developing countries, as it may help create systems with low inputs that provide the desired gains in services.

The reductions of each intensity term from the adapted Kaya identity, can be divided into supply- and demand-side options. Some engineering efforts to develop more efficient technologies and processes that decrease material and product intensities are part of the supply-side. In turn, for demand-side, consumers may choose to acquire efficient products or reduce their demand for certain services. Furthermore, government policies can aid supply- and demand-side options, with regulations for efficient products' supply, and stimulating demand for efficient technologies through consumer information policies or subsidies. Many of these strategies are highlighted by the IEA (2020*b*). Both supply and demand actions may be led by nations and groups of nations that develop policies and guidelines, e.g. by setting minimum performance standards of the devices sold (supply-side) or by increasing the availability of public transport (demand-side). The alternatives will be better quantified if the end-goal is clear, which is the adequate service provision.

1.5 Service quantification and framework used

The exploration and assessment of services is useful for informing national energy planning activities, for three main reasons:

1. *The quantification conciliates simplistic primary energy models and close understanding of energy uses.* The increasing complexity downstream in the energy system, allows for almost limitless consumer expressions of how to receive energy services e.g. mobility provided by walking, cycling, using a scooter, using public transport, using a train, driving, being driven or a combination of some or all of the aforementioned options. In contrast and for simplicity, energy planning models collect and use a somewhat limited and relatively uniform set of primary and final energy sources globally (e.g. coal, gas, electricity, wind, solar, hydro) with less information being collected to derive energy uses; this increases the uncertainty of any calculation near end-uses.

2. *Modelling service delivery allows for demand to be understood as cultural norms are included and replicated in energy planning.* This is because service delivery is more closely aligned to the cultural and physical needs of consumers than primary or final energy, e.g. Finnish thermal comfort with the use of saunas requires 5 % of household energy house (Jensen, 2017). Misunderstanding cultural norms and needs is perhaps part of the reason why so many attempts to deliver energy projects in developing countries fail (Hirmer and Cruickshank, 2014).

3. *Tracking the delivery of services to consumers allows energy planners and policy makers to reduce energy demand without affecting, and even increasing, well-being.* The complexity of the energy system is in constant flux. This is a result of the large range of energy conversion devices, passive systems, energy pathways and energy services, many of which are not included in country statistics. This means that although primary energy is linked to well-being outcomes, it cannot be guaranteed that an input of primary energy to specific energy pathways at one end, will deliver the same level of energy service and well-being to the consumer at the other end. Steinberger et al. (2020) have even shown well-being improvements related to life expectancy are more linked to residential electricity improvements (related to final energy), than to primary energy. Thus, finding the most effective routes to deliver well-being while reducing energy demand is desirable. This thesis refers to such routes as adequate service provision.

The schematic shown in figure 1.3 has been created to showcase the scope of the thesis. Henceforth, it will be referred to as the *resource chain*. The resource chain traces from primary energy (and carbon emissions), through final and useful energy conversion processes, and materials and products, to the deliver of services. This thesis postulates that the provision of services is directly linked to human development outcomes and well-being. Furthermore, the fact that service provision is located nearer development in the resource chain, leads to the hypothesis that understanding and assessing service provision will provide more insight on human development outcomes, than the current focus on primary and final energy. The term human development will be used interchangeably with the term human well-being for the purposes of this thesis, insofar as they refer to the improvement of human lives.

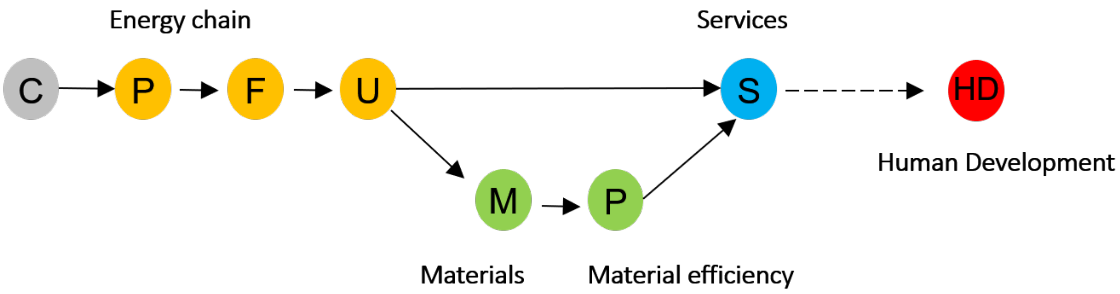

Fig. 1.3 Resource chain to provide services. Sources (C) such as carbon, solar, biomass or others undergo transformations from Primary (P in energy chain), Final (F) to Useful (U) energy using conversion devices and passive systems. U gets subdivided and goes to Services (S) either as energy or as Materials (M) that turn into Products (P in material chain). Services are then used to support Human Development (HD). The dashed line from S to HD refers to changing from resource transformations to the outcomes produced for the population.

1.6 Aims of this research

Maintaining and increasing well-being in developed and developing countries, while reducing emissions by generating alternative ways to supply the desired services, are some of the biggest challenges for implementing just climate change solutions. This thesis suggests that by improving the understanding of the resource transformations which deliver services, societies can better plan for their future resource needs and avoid damaging carbon emissions. The overall research question posed by this thesis is the following:

> **What insights about human well-being and emissions reduction can be gained by exploring and quantifying service provision?**

This thesis will focus on quantifying the services used, the resources involved in supplying them, the relationship between services and well-being outcomes, and the key policy repercussions of changing practices. A mix of quantitative and qualitative methods are used, mainly focusing on the former by doing statistical analyses and models. The geographical scope of this thesis is wide with two chapters with an international scope and one with a country-level scope. Databases containing several countries at varying development levels are used, which have been obtained from different sources such as international organisations, public online databases, and national databases. Additionally, an example will be presented for one developing country to gather extendable insights on country-level conditions.

Thesis structure

The remainder of this thesis is structured as follows: Chapter 2 presents the reviewed literature relevant to the aims of this work and concludes by outlining the research questions posed related to the gaps identified. Chapters 3-5 present the analytical pieces of work related to the research questions identified, each chapter contains the methods used and the rationale for selecting them, the results obtained and a discussion of the findings. Chapter 6 answers the research questions by building on the findings from the previous sections and identifies the areas that require further work. The remaining pages contain appendices that contain relevant clarifications for Chapters 3-5, along with the references.

2

Literature review

In this chapter, the prior academic research and broader knowledge is reviewed, relating to: the structure of resource chains, service provision and well-being in section 2.1; the links between energy use, climate targets and development outcomes in section 2.2; and policy for energy transitions in section 2.3. The literature review provides a comprehensive appraisal of existing academic work and then identifies key gaps in knowledge. The final section 2.4 describes these gaps and presents three research questions which unpin the research in this thesis.

2.1 Well-being, resource chains, services and the links between them

This section introduces ways of measuring development levels for different countries, the factors that have led some countries to achieve higher levels of well-being than others, how resources play a role in such levels of well-being and what aspects are important for developing countries to reach higher levels of well-being under climate constraints.

2.1.1 Measuring well-being and international development levels

The quantitative study of development or well-being identifies sets of indicators that represent desired well-being outcomes. To define such aspects, Brand-Correa and Steinberger (2017) compare two schools of thought to define well-being: hedonic, which refers to maximising pleasure and individual well-being (with the best example of an indicator being Gross Domestic Product- GDP), and eudaimonic, which focuses on the individual in his or her social context. Brand-Correa and Steinberger conclude that the eudaimonic approach is better-suited for studying well-being in sustainability research, since individual flourishing depends on the context, which includes political systems, and inter-generational goals.

Table 2.1 shows examples of well-being indicators, that serve to illustrate the aspects considered by each indicator. The indicators shown are mostly eudaimonic, except for when they refer to income. The indicators include the years for which indicator data is available, and the indicator type. The indicator type shows whether the indicator can be estimated on its own or whether it is calculated through an aggregation of others. The indicators formed by aggregating others are referred to as compound indicators in this thesis.

Non-aggregate development indicators consider a wide range of aspects such as health, education and income. Apart from these, the UNDP (2020*b*) has recently included gender, mobility and communication, environmental sustainability, trade and financial flows, and work, employment and vulnerability. Table 2.1 shows examples of such non-aggregate development indicators. The inclusion of all these topics illustrate the different dimensions that are associated to well-being outcomes.

Table 2.1 Common international development indicators.

Development Indicator (unit)	Type	Years available	*Source*
Life expectancy at birth, total (years)	Non-aggregate	1960-2018	UNDP (2020*b*) Zijdeman and Ribeira da Silva (2015) Riley (2005)
Average total years of schooling for adult population (years)	Non-aggregate	1870-2020	UNDP (2020*b*) Roser (2020)
Expected years of schooling (years)	Non-aggregate	1990-2020	UNDP (2020*b*) Roser (2020)
GNI per capita, PPP (constant 2011 international $) (Rate)	Non-aggregate	1990-2020	UNDP (2020*b*) Roser (2020)
Net migration rate (per 1,000 people)	Non-aggregate	1990-2020	UNDP (2020*b*)
Mobile phone subscriptions (per 100 people)	Non-aggregate	1990-2020	UNDP (2020*b*)
Remittance inflows (% of GDP)	Non-aggregate	1990-2020	UNDP (2020*b*)
Natural resource depletion (% GNI)	Non-aggregate	1990-2018	UNDP (2020*b*)
Total unemployment (% of labour force)	Non-aggregate	1991-2019	UNDP (2020*b*)
Human Development Index	Aggregate	1990-2020	UNDP (2020*b*)
Historical Index of Human Development - including GDP indicator	Aggregate	1870-2015	Prados de la Escosura (2015)
Historical Index of Human Development-without GDP indicator	Aggregate	1870-2015	Prados de la Escosura (2015)
Inequality-adjusted Human Development Index	Aggregate	2010-2020	UNDP (2020*b*) Roser (2020)
Gender Development Index (GDI)	Aggregate	1995-2019	UNDP (2020*b*)
Gender Inequality Index (GII)	Aggregate	1995-2019	UNDP (2020*b*)
Social Progress Index	Aggregate	2014-2020	Stern et al. (2017) Social Progress Imperative (2019)
Multi-dimensional Poverty Index	Aggregate	2014-2019	UNDP (2020*b*)

Aggregating development indicators addresses the changing understanding and quantification of the factors behind well-being, despite the difficulty to interpret such indicators. A well-known compound indicator is HDI, which was created in 1990 by the UNDP and has been influenced by the capabilities approach proposed by Sen (1999) and Nussbaum (2000). HDI has three main components: life expectancy, education and income. All components are equally averaged to evaluate HDI. Inequality, understood as the relative difference between the richest and poorest people in a nation, was identified as a drawback for HDI. The methodology for HDI was then changed in 2010, with the level of inequality in a country being discounted from the average values of each dimension. The resulting indicator was re-labelled as Inequality-adjusted Human Development Index (IHDI). The inclusion of gender has led the UNDP (2020*b*) to create the Gender Development Index (GDI), which is a ratio of female to male HDI values UNDP (2020*a*), and the Gender Inequality Index (GII), which considers female reproductive health, and both female and male labour and empowerment. A more recent indicator is the Social Progress Index (SPI) (Stern et al., 2017), which excludes economic measures on purpose to disentangle progress associated to economic factors. The SPI focuses on three dimensions: basic human needs, foundations of well-being and opportunity; quantifying each dimension with over ten different indicators e.g. the human need dimension is quantified with dimension related to nutrition, water, shelter and safety. Finally, the Multi-dimensional Poverty Index (MPI) considers household and individual deprivations surrounding health, education and standard of living (UNDP, 2020*b*). The background information to measure each dimension of MPI should come from the same survey, unlike HDI and IHDI, which use different sources. The use of multi-indices in compound indicators has the disadvantage of having low reliability of the underlying variables (Nussbaumer et al., 2012), as well as subjective component weights. Such subjective weights also mean that results considering compound indicators are less easy to interpret.

The available compound indicators to measure development highlight the difficulty in choosing which conditions of human living to consider and measure. There are different stages that can be identified, from the indicators that try to define and measure basic needs (e.g. SPI), to those that measure deprivation (e.g. MPI), to long-term outcomes such as life expectancy (e.g. in HDI).

There are dimensions of the development indicators that are closer to specifying parts of the resource chain, yet they are few, and only one indicator mentions a low-carbon path. Some indicators allude to the part of the resource chain of end-use devices, e.g. the asset ownership indicator of MPI expressed as “the household does not own more than one of these assets: radio, TV, telephone, computer, animal cart, bicycle, motorbike, or refrigerator, and does not own a car or truck" (Alkire et al., 2020). Some compound indicators almost allude to services when creating indicators of living conditions for some of their dimensions, e.g. in the usage of clean fuels and technology for cooking in the SPI, which is close to the service of sustenance, and suggests that the reference to 'clean' fuels in the SPI means low-carbon ones.

The indicators described above have made efforts to identify and include several dimensions that drive development. However, many indicators fail to include two key aspects which are critical to achieve climate-compatible development: the addition of resource transformations and the inclusion of climate dimensions.

The challenge of including resource transformations in development indicators is choosing both indicators and relevant parts of the resource chain. Thus, many of those transformations are disregarded up until the point where there is either a tangible, measurable or generalisable outcome, e.g. shelter, which is tangible, measurable even as a binary variable, i.e. 'yes or no', and generalisable because there are many ways to provide shelter. Even so, shelter is not the only service provided by a house or a building, which increases the difficulty in assessing each service separately. Different combinations of resources could provide shelter, from a house made of wood, to a steel and concrete building. Thus, including different resource transformations to provide different types of shelter is hard, because of the wide variety of steps available. However, under climate constraints, some ways of providing shelter have lower emissions than others. So, finding ways to evaluate low-carbon resource transformations alongside development is needed.

2.1.2 Country resource chains and development

Resource chains, which convert energy and materials to services, play a key role in securing improved development and well-being outcomes in nations. Yet, the level of maturity of resource chains, across different societies, varies widely. In countries with low levels of development, resource chains are simple and rely mostly on biomass and animal muscle power. Smil (2010) points out that, to develop, countries that typically relied on biomass and muscle power found reliable sources of additional energy, usually at higher density. Smil (2010) further acknowledges that transitioning between different energy sources is a slow process, that can take many decades. Countries that rely on biomass and muscle power are still common today, so their development needs to occur using a different path with lower emissions.

Critical in such transitions are the creation of skilled work-forces, financing mechanisms and infrastructures related to energy, transport, buildings and industry (Modi et al., 2005; Pachauri et al., 2012). Developed countries, with higher per capita income levels, tend to have greater shares of energy use in the residential, commercial, public and transportation sectors, while energy use in developing countries, with low per capita income levels, is dominated by residential and industrial sectors (International Institute for Applied Systems Analysis, 2012). The lower levels of industrial energy use in developed nations is facilitated by imports of manufactured goods made in developing countries (Gutowski et al., 2017).

The development of energy, transport and industrial infrastructure is well underway in many African and Asian nations with the aim to increase the service provision levels to people, e.g. the fraction of floor area additions in Sub-Saharan Africa and India is expected to be half of the global total built by 2070 (IEA, 2020*b*, Chapter 3). However, current development trajectories are set to follow the historical development pathways of industrialised nations, using the extraction of fossil fuels to deliver increased service provision, but in doing so, locking in increasing carbon emissions (Unruh, 2002, 2009). This already occurs with emissions associated to construction materials in Asia and other developing countries (IEA, 2020*b*, Chapter 4).

The challenge facing developing nations, and the global community, is to find ways to increase service provision and improve development outcomes, which are compatible with climate mitigation targets and the local country contexts.

2.1.3 Studies linking some part of the resource chain and development

There is progress in linking some aspects of service provision, yet it is hardly framed as service provision, since studies tend to focus on aggregate measures. Usually, a part of the resource chain is tracked using aggregate indicators with development or well-being. The studies using such indicators may cover more than one indicator for both a fraction of service provision and development. Service provision indicators used have included some form of energy (Mazur and Rosa, 1974; International Institute for Applied Systems Analysis, 2012; Nussbaumer et al., 2012; Kander and Stern, 2014; Steinberger et al., 2020), materials (Gutowski et al., 2017; Rao and Min, 2018) or emissions (Steinberger and Roberts, 2010; Lamb et al., 2014; Steinberger et al., 2020). In turn, development has been measured using indicators such as GDP, HDI, or life expectancy (as described in section 2.1.1). Studies using development indicators can be divided into areas of focus such as: economic outcomes (Steinberger and Roberts, 2010; International Institute for Applied Systems Analysis, 2012; Kander and Stern, 2014), productivity (Karekezi et al., 2012), living standards (Mazur and Rosa, 1974), and social outcomes (Mazur and Rosa, 1974; Cecelski, 2005; Steinberger and Roberts, 2010; Steinberger et al., 2020).

The links between energy and well-being were studied as early as 1974 by Mazur and Rosa, who correlated energy (specifically electricity) consumption with economic and well-being indicators (e.g. health, education and life satisfaction, gross national product per capita, and device ownership such as telephones or automobiles) in 55 countries with different development stages. The study found strong relationships among the indicators and was fundamental in showing how well-being indicators could be quantitatively studied.

A number of academics have explored the link between development, measured using HDI, and specific stages along the resource chain, such as energy consumption per capita (Martínez and Ebenhack, 2008), primary energy (Steinberger and Roberts, 2010), electrification (Attigah and Mayer-Tasch, 2013; Alstone et al., 2015), primary energy footprint which considers trade (Arto et al., 2016), and domestic material consumption (Gutowski et al., 2017). These studies show strong correlations between the level of development and the consumption of energy and materials, across most nations.

Emissions at different stages of the resource chain have also been correlated with HDI and other development indicators such as life expectancy, finding strong correlations. Among the indicators used to quantify emissions are: total emissions (Steinberger and Roberts, 2010), and consumption-based CO_2 emissions accounts (which include the emissions associated with consumption of local production and imported goods) (Steinberger et al., 2012; Lamb et al., 2014). Lamb et al. (2014) also identify common drivers of country emissions, e.g. having similar climates, which can guide low-carbon development in shared country contexts.

Economic growth is a common measure of development used to compare countries. Indicators of economic growth show correlations with energy use for specific nations as shown by Kander and Stern (2014), and groups of nations as shown by Steinberger and Roberts (2010) and Lamb and Rao (2015). The International Institute for Applied Systems Analysis (2012) describes the economic growth as having a bi-directional relationship with energy services, where “good energy services are a condition for economic growth, while economic growth will increase energy services’ demand". Other studies argue that instead of focusing on economic growth alone, focusing on increasing energy use and technologies that facilitate productive activities can make economies flourish (Karekezi et al., 2012).

The studies discussed earlier provide evidence that the relationship between energy or emissions and well-being fails to hold at higher levels of income, energy and emissions (Martínez and Ebenhack, 2008; Rao et al., 2014; Lamb and Rao, 2015; Akizu-Gardoki et al., 2018). Rao et al. (2014) describes this as a saturation effect, whereby increasing levels of emissions per capita provides decreasing returns in HDI levels. One consequence of this effect is that sufficient levels of HDI can be achieved with relatively low levels of energy demand and emissions generation, offering some hope that climate-compatible development is possible. Akizu-Gardoki et al. (2018) has shown that this decoupling effect, between energy and development levels appears to occur in both high-income energy-efficient countries and low-income countries.

Inequality associated with economic and resource access is fundamental for energy and development research, given that the uneven distribution of wealth between and within countries is associated with uneven emissions and lower well-being outcomes. Wealth inequality translates into inequality in energy consumption and emissions at several levels, including internationally, with wealthier countries generating the highest per capita emissions (Steinberger et al., 2010; Ivanova et al., 2015; Teixidó-Figueras et al., 2016); at national level, where the richest income groups account for the majority of energy use and emissions (Oswald et al., 2020); and within different income groups of different nations, with wealthier groups accounting for higher energy consumption and emissions (Oswald et al., 2020). There is also a feedback loop, with climate change impacts being associated with increasing income inequality (UNDP, 2019, Chapter 5). This effect also extends negative health and education impacts, e.g. low agricultural yields that affect nutrition, which in turn can complicate other illnesses (UNDP, 2019).

Economic indicators have shortcomings, as identified by Pachauri and Spreng (2011), who argue that economic indicators linked to levels of energy access and energy poverty, measured using household expenditure, do not reflect the situation in developing countries adequately, where informal markets operate. Further, Brand-Correa and Steinberger (2017) identify economic growth as one of the one most representative indicators of hedonic well-being. However, economic growth is less useful for studying sustainability transitions because it does not account for the well-being of all people with their societal context. To address the shortcomings of economic indicators, specific energy poverty indicators (Nussbaumer et al., 2012), material requisites (Rao and Min, 2018), and social factors which reflect non-economic indicators have been identified e.g. gender, education levels, lifespan or political participation (Cecelski, 2005; Social Progress Imperative, 2019).

The relationship between energy, emissions and well-being has been studied using some non-economic indicators that reflect human needs or energy measures closer to the end user. The saturation phenomena for energy consumption with both life expectancy and basic needs was confirmed by Lamb and Rao (2015). Their measure of basic human needs included several sub-indicators (health, sanitation, food, shelter, and education, all equally weighted). In turn, Steinberger et al. (2020) explored correlations of life expectancy with human needs, final energy and emissions. The measures of human needs include food supply, while final energy in the form of electricity is used as a proxy for some services. Steinberger et al. find strong dynamic coupling between the indicators, with primary energy strongly correlated to income but only accounting for a quarter of improvements in life expectancy. In contrast, residential electricity results strongly correlated with life expectancy. Steinberger et al. conclude that the attainment of human development at one point in time does not mean the dynamics are coupled over time. Lamb (2016) also explores human needs, yet analyses them in a disaggregated manner to compare human needs to current and estimated trajectories of energy and emissions. Lamb only includes countries in the so-called Goldemberg corner-which are those with low energy use and low emissions, but with high life expectancies. Lamb observes that there is room for improving many of the needs identified, such as sanitation, while electricity access and services provided by it seem to be widespread.

The observations of Lamb and Rao (2015); Lamb (2016) and Steinberger et al. (2020) have made important contributions in the application of non-economic measures. However, the services provided by the aggregated indicators that Lamb and Rao (2015) and Steinberger et al. (2020) use are not easy to discern, e.g. the indicator for human needs by Lamb and Rao encompasses many services, but from the results, one cannot identify the effect of each one in the total correlation. Further, the electricity measure used by Steinberger et al. may be used for several services (e.g. sustenance, thermal comfort), while other services needed cannot be included (e.g. transport). The authors recognise some of these limitations and attribute some of them to the lack of data availability. In the only study that disaggregated human needs (Lamb, 2016), the author advises that disaggregating multiple indicators and development goals leads to the understanding of tangible outcomes.

The studies described in this section have made important contributions towards understanding the links between resources, emissions and well-being. However, they stop-short of providing insight into the closer connection between the provision of specific services and well-being. Primary and final energy or accounts of emissions are related to the energy and material inputs required to deliver services, yet, are distanced from services by the energy conversion and material processing steps. Each of these steps is inefficient, including energy and material losses, and thermodynamic irreversibilities. This means that increases over time in primary energy do not necessarily translate directly to improved service provision. Improving the understanding of service delivery, and focusing on the options which deliver adequate services, may be a better strategy for delivering well-being and development outcomes.

2.1.4 Including services and linking them with well-being

There are some advances in the literature that are closer to measuring the provision of certain services that deliver well-being at low environmental impacts. This strand of research was pioneered by Goldemberg et al. (1985), who listed basic activities (e.g. cooking, floor space, transport, manufacturing and agriculture) and proposed that by shifting to high quality energy carriers and improving efficiency, living standards could increase without increasing energy use per capita.

The studies that include basic activities also investigate the minimum amount of energy needed for well-being (Goldemberg et al., 1985; Chakravarty and Tavoni, 2013) or decent living (Rao et al., 2019). The values estimated for final energy needs are: 30 GJ/cap/year (Goldemberg et al., 1985), 25 GJ/cap/year (Chakravarty and Tavoni, 2013) and 12-24 GJ/cap/year (Rao et al., 2019). Rao and Min (2017) argue that various metrics focus on measuring the outcomes of well-being, rather than the drivers or necessary conditions of it. Thus, Rao et al. (2019) pioneer the use of a bottom-up study with explicit carbon constraints (focusing on India, Brazil and South Africa), including particular conditions and demand for certain devices. They called their set of material pre-requisites 'Decent Living Standards' (DLS). The standards are composed of physical well-being (nutrition, shelter, living conditions, clothing, healthcare and air quality) and social well-being (education, communication, information access, mobility and freedom to gather/dissent). Rao et al. conclude that mobility requirements dominate construction energy and food preparation has the second-largest demand for energy, with the diet type impacting the amount of energy needed.

An extension of the DLS modelling was carried out by Millward-Hopkins et al. (2020) to investigate the minimum global energy needs, focusing on material requirements and final energy. Millward-Hopkins et al. observe that global final energy consumption has the potential to be reduced to levels similar to the 1960's, while providing adequate levels of well-being for the world, by capping the final energy of those countries who exceed well-being limits and increasing access to the 4 billion people who live in poverty. The study is fundamental for showing that minimum material and energy requirements can be achieved under current energy supply. Millward-Hopkins et al. also include some regional aspects in energy needs (e.g. heating or cooling degree-days) and the population distribution (e.g. the population's age to consider their diets or number of schools needed).

The studies discussed have advanced the understanding of material and energy needs for well-being and proved that it is possible to provide decent living for all. However, final energy estimates by Rao et al. (2019) and Millward-Hopkins et al. (2020) use a set of predetermined devices and efficiencies, which assume that device needs are common to all individuals. A more nuanced approach might be required depending on contexts (e.g. cooking practices). Rao et al. (2019) recognise that that the DLS need to be met by individuals and communities in countries, whose requirements and culture may differ. Additionally, the studies assume that there is a rapid scaling-up of technologies, which is not in line with technology diffusion that has been historically observed, where the rates of adoption within and between countries presents varied dynamics (Stoneman and Battisti, 2010).

Studies of the link between resources and well-being are increasingly acknowledging the role of services. For instance, Kalt et al. (2019) recognise that services mediate between achieving a desired function and providing a benefit for human well-being. However, including services is complicated given their quantification, so proxies tend to be used instead, e.g. residential electricity (Steinberger et al., 2020).

Quantifying and defining services has been the subject of academic research. The research has included the conceptualisation of services by Fell (2017), the quantification of some services (e.g. sustenance, thermal comfort, among others) based on global energy flows Cullen et al. (2011), and the argument that decoupling energy use from well-being requires the understanding of services by Brand-Correa and Steinberger (2017).

The concept of services has also been linked to other fields of knowledge around the systems of the Anthropocene. Kalt et al. (2019) analysed the different research contexts where the concept of energy services is included and categorised them as: energy chain, energy demand, well-being and entrepreneurial contexts (considering energy service companies). Their classification illustrates that the concept of services has been increasingly embedded in the literature. Kalt et al. also link services to socio-economic stock-flow relations- better known as socio-economic metabolism or metabolic systems.

Metabolic systems have been described by Pauliuk and Mu (2014) and Pauliuk and Hertwich (2015) as a useful paradigm to study the biophysical basis of human society considering biophysical structures of society (Haberl et al., 2004), which include “human-controlled in-use stocks such as infrastructure, buildings, vehicles, machines and other fixed capital, consumer products, but also our own bodies, and of socioeconomic metabolism, which describes the industrial processes, market activities, commodity flows, and exchanges with nature to build, maintain, and operate the in-use stocks" (Fischer-kowalski and Haberl, 1998). Metabolic systems have proven informative due to the inclusion of system dynamics, which explore how different variables interact with each other in complex systems (Forrester, 1997). In a white paper, Carre and Wegener (2018) identify key parts and dynamics of metabolic systems, and propose research questions focusing on urban metabolism. Such research questions include consumption patterns of energy and other resources, behavioural analyses, the dynamic linking of stocks and flows using spatio-temporal components, and the connection between metabolism and public health. Although Carre and Wegener focus on urban metabolism, the questions proposed involve a systematic understanding of underlying dynamics that also affect non-urban settings e.g. agricultural produce will reach urban areas, but are grown in rural ones. Carre and Wegener (2018) mention the multidisciplinary aspects of their proposed research which, unknown to them, also refers to services. Thus, standardising concepts in many academic disciplines seems necessary (Carre and Wegener, 2018; Kalt et al., 2019).

Summary from section 2.1

Climate change is accelerating the need to study how to preserve and increase human well-being with lower emissions. There has been progress in defining some human needs that provide well-being for the many in a measurable way, which has included quantifying the minimum amounts of energy required for a decent life. Additionally, indicators of resource use including energy, materials and emissions have been correlated to well-being indicators, showing strong correlations at varying degrees and with different levels of coupling over time. Such correlations show a saturation phenomenon, where higher levels of resource use, do not deliver higher levels of well-being. Despite the advances in this area of research, some areas remain to be addressed. These include investigating the relationship between resources and well-being in a systematic way by including resource transformations up to services, and standardising terms from different academic disciplines to encourage the much needed multi-disciplinary research.

The quantification of service provision is hindered by the scarcity of data with enough granularity regarding resource transformations, as well as an overall data scarcity for developing countries. With the pressing need to deliver climate compatible development, there is a gap to identify measurable resource provision indicators at an international scale and link them to well-being. This will increase the evidence of the role that services play in well-being and the correlations between service provision and development.

2.2 Achieving climate-compatible development

Several countries have recognised the need to address climate change and have made pledges to limit GHG emissions linked to the Paris Agreement, which involve setting future emission targets and exploring the necessary actions required to meet them. Committed actions are recorded as Nationally Determined Contributions (NDC), administered by the United Nations Framework Convention on Climate Change Secretariat (UNFCCC, 2019). The NDC are submitted every five years and should include country pledges to reduce emissions based on domestic circumstances and capabilities.

Various models are used to evaluate different interventions on resource use and their environmental impacts. Some of the models are global or sector-based that evaluate different pathways and emission mitigation potentials. Many of these types of models are those belonging to Integrated Assessment Models (IAMs), e.g. the World Energy Model used by the IEA (IEA, 2020*d*). IAMs are useful because they can produce economic and technically feasible results aligned to policy recommendations. Given their scope, IAMs have also been used by the Intergovernmental Panel on Climate Change (IPCC) to evaluate the Shared Socioeconomic Pathways (Riahi et al., 2017), which are five different socioeconomic scenarios for climate mitigation and adaptation. However, IAMs are usually focused on the supply-side of different sectors, while demand-side measures are included as exogenous inputs, such as economic growth, demographics and some technological developments in the IEA's IAM (IEA, 2020*e*). Additionally, Cronin et al. (2018) identifies that IAMs that make climate projections from energy systems need to include the study of regional impacts in developing countries.

The use of trade information in models that quantify resource use has been the subject of academic research (Rao and Baer, 2012; Oswald et al., 2020; Millward-Hopkins et al., 2020). Such research is enabled by the availability of data for trade stocks and flows, which includes the Global Trade Analysis Project (GTAP) (Mcdougall and Lee, 2002; Aguiar et al., 2016). GTAP considers over 110 countries and contains input-output tables using monetary units, leading to detailed results at a global level. However, given the monetary units of GTAP, Oswald et al. (2020) acknowledges that there is some uncertainty in converting them to energy and material units.

Other models and modelling frameworks are used to make country-level decisions on selected topics. Some examples of the models are LEAP (Long-range Energy Alternatives Planning System) (Heaps, 2018), to produce emission reduction strategies from different sectors, which is widely used to create NDC; and ONSSET (Mentis et al., 2015), which focuses on electrification using geolocation information (e.g. Geographic Information Systems- GIS). These models are useful for evaluating technical solutions subject to country conditions and predict their energy, environmental and sometimes economic impacts. They rely on databases of prescribed parameters, which may be altered if needed, e.g. the average efficiency of household appliances in LEAP. The models commonly evaluate and present macro-economic conditions and supply-side solutions, while demand-side solutions tend to be dependant on modifying inputs, e.g. changing the efficiency of certain devices when the model is run.

The models discussed earlier have provided valuable insights for energy systems and policy-making in light of climate change. However, one of the challenges of the models is making representations that are accurate enough for the desired goals e.g. by adjusting the input parameters of LEAP or ONSSET to reflect known local conditions. The data inputs that reflect country conditions must be accurate, yet, there is no assurance that this is the case with developing country data, which is scarce (Wilson et al., 2012). Heaps (2018) also acknowledges that, given the modelling complexity, several people or organisations are required to create, update and use the models. This may limit the knowledge of local stakeholders on how to action the recommendations from the models, unless they are involved in the process (Heaps, 2018).

Since demand-side energy use is closer to services, some studies have either highlighted the importance of considering demand-side solutions (Wilson et al., 2012) and have created or modified models accordingly. Among them is the global demand-focused IAM by Grubler et al. (2018), where combinations of activity levels and energy intensity provide enough levels of services, which satisfied both services needed and the limited temperature increase of 1.5 °C. Their work serves as proof that demand-side options focusing on services have potential for mitigating climate change.

The models discussed previously have shown that if sufficient and accurate information is gathered to make models, such as device efficiency, energy uses, population characterisation, among others, the accuracy of the predictions is improved. However, obtaining detailed information is a challenge, given the data scarcity observed, in many cases for developing countries. Additionally, model developers have clarified that, the involvement of local stakeholders in the creation of models is critical for ensuring the model recommendations are taken up.

2.2.1 End-use devices: an important part of the resource chain for climate-compatible development

Engineering principles are used to create end-use devices that allow for energy to be transformed into useful energy and then used for service provision e.g. heaters and lighting devices for thermal comfort and illumination. Grubler (2012) argues that there is a lack of knowledge of useful energy and services, which is limiting the understanding of long term energy transitions. He also elucidates that there may be biases in understanding previous transitions, given their reliance on primary and final energy accounts. Quantifying useful energy through end-use devices can be complex given the varied configurations of energy provision, device efficiencies and user activity patterns (e.g. frequency of use, maintenance, among others). Paoli et al. (2018) argues that monetary transactions have helped to make primary and final energy estimations, but because useful energy does not require any such transaction, the laboursome collection of data on devices and their use is required instead. The effort to collect such data is worthwhile, since Wilson et al. (2012) find that efficient end-use technologies have large potential emission reductions and provide higher social returns on investment than energy-supply technologies.

The concept of useful energy was defined in 1909 (Ostwald, 1909), yet studies are uncommon, highly academic, and rarely follow a standardised method. Examples of useful energy analyses were only found for the European Union (EUROSTAT), Colombia (Toro et al., 2019), Brazil (Ministério de Minas e Energia, 2005), a mix of 15 countries (Stercke, 2014) and the UK (Paoli et al., 2018). Paoli et al. (2018), in particular, is exemplary for including detailed methods for estimating the current and practical limit efficiencies for end-use devices and a rigorous uncertainty analysis, that depended on detailed UK household energy surveys. An increased awareness to make useful energy analysis has been shown in Latin America (Gonzalez Benitez, 2017), but as yet, few results have been published, while Brazil discontinued their useful energy surveys and analysis due to data uncertainty (Paoli et al., 2018). This shows how challenging it is to make updated useful energy estimations.

Varied methods and models have been employed to calculate useful energy. Paoli et al. (2018) identify the use of four main data-gathering methods for useful energy quantification in different sectors (including industry, buildings and the commercial sector): metering and auditing, direct surveys, engineering models and statistical models. These methods rely on varied degrees of detail of data availability, breakdowns into the necessary categories or knowledge of statistical relationships between the variables. Paoli et al. also identify that the inclusion of uncertainty in any of these methods tends to be uncommon.

The argument that improving end-use device efficiency has a high potential for lowering energy and emissions has been made for some time. Over two decades ago, Gilli et al. (1996) assessed specific technology efficiencies at national and regional levels, finding global efficiencies of 30% for the conversion to useful energy, and suggesting that demand-side management could be useful for reducing energy use. However, progress has been slow, as confirmed by Wilson et al. (2012), with many efforts to increase device efficiency still in progress. For instance, end-use devices for specific services have been the focus of several academic, public and private institution studies, many of them for developing countries e.g. cooking (International Energy Agency, 2015; United Nations Foundation, 2019; Sepp, 2014), lighting (Global Off-Grid Lighting Association, 2019), and space heating and cooling (Mastrucci et al., 2019). Further, information on device efficiency has been compiled by CLASP (2020*a*) to assess the potential for energy and emissions reductions through efficiency measures. Government involvement in the creation of efficiency measures is via the implementation of Minimum Energy Performance Standards (MEPS). MEPS are a type of policy instrument aimed at removing poor-performing devices from the market and driving efficiency improvements across a range of end-use devices.

Apart from reducing energy and emissions, improving the efficiency of end-use devices can bring additional benefits (Wilson et al., 2012), especially in developing countries (Karekezi et al., 2012). Karekezi et al. (2012) and Hirmer and Guthrie (2017) discuss that some benefits of such efficiency improvements are: lower cost of energy sources, lower time spent collecting biomass for burning, a lower burden for women and children who would have collected biomass themselves, and reduced respiratory problems from biomass or kerosene burning, increased perception of personal security, among others. Furthermore, the type of devices whose efficiencies can be considered are beyond household ones, since businesses and income-generating activities also require increased efficiency (Karekezi et al., 2012).

2.2.2 The research frontier beyond end-uses

A separate group of academics have explored a concept known as useful exergy (a measure of available work), which refers to the overall societal efficiency and connections with economic growth. The calculation of useful exergy involves first performing a useful energy balance and then converting the energy values to exergy (e.g. using Carnot's Law to calculate the available work in heat flows). Measuring exergy can be used to compare the efficiency improvement potential of different technology options. Examples of exergy applications are the following: Gilli et al. (1996) calculated useful energy and exergy efficiencies of several technologies e.g. water heaters, air conditioning, different transport modes, at a regional and global level. Cullen and Allwood (2010) performed an analysis of global exergy efficiency for all conversion devices e.g. engines, burners, coolers. Finally, Heun and Brockway (2019) undertook an extensive bottom-up data gathering exercise to map the exergy flows and efficiencies for Ghana, one of the few examples of useful exergy studies in a developing country. Overall, useful exergy studies, shed much light on the functioning of the entire energy system in a country or region, including the interactions between energy and materials, but focus less on the end-use devices, and their interactions with people or how they deliver services.

A common theme across all useful energy and useful exergy studies is the challenge of finding accurate data of energy flows and efficiencies related to end-use devices. Estimating the average efficiency of a diesel engine or light device, across a nation or globally, involves much uncertainty (Paoli et al., 2018; Paoli and Cullen, 2020). Allocating final energy flows to end-use devices, such as final energy in the form of electricity to different appliances, is difficult even in countries that collect detailed household information, such as the UK (Paoli et al., 2018), whereas detailed information in other sectors is even scarcer e.g. detailed electricity allocation in industrial or commercial applications. This implies that the collection of bottom-up data in developing countries will be even more laboursome and uncertain, given the lack of information on even final energy accounts.

2.2.3 The use of national household statistics for service quantification

Routine data collection on specific country conditions is commonly carried out by bodies of national statistics e.g. the Uganda Bureau of Statistics (2012); private companies, e.g. an off-grid lighting report (Heemskerk et al., 2014); researchers, e.g. interviewing Ugandan villages (Hirmer and Guthrie, 2016); and other stakeholders, e.g. a UN Habitat report on energy consumption (Kazoora et al., 2015). The data collected can be used either for specific purposes, such as the studies done by researchers, private companies and NGOs, or for keeping track of general living conditions of the population, such as national surveys. The data collected depends on the research question and which topics the samples collected should be representative of e.g. the population in national statistics or all possible manufacturers of a technology e.g. Heemskerk et al. (2014).

Understanding energy transitions in households requires knowledge of local service provision and detailed country data. Several academics have hypothesised that households would substitute energy sources as newer or better ones became available. This concept is referred to as the 'energy ladder' and attributes changes in energy sources used to increases in income and socio-economic conditions (Hosier and Dowd, 1987; Nansaior et al., 2011; Van Der Kroon et al., 2013). However, the concept has not been upheld in more recent studies, which show that several energy sources are used simultaneously. This is known as 'fuel stacking' (Masera et al., 2000; Peng and Pan, 2010; Ruiz-Mercado and Masera, 2015; Bisaga and Parikh, 2018; Choumert-Nkolo et al., 2019) or 'energy staircase' (Harrison and Adams, 2017). It is therefore important to integrate this concept of fuel stacking when analysing service provision in developing countries.

Estimating energy transformations requires country-level information, e.g. household surveys that are representative of the population, may be used for estimating useful energy. National household surveys are undertaken regularly in many countries, including developing ones, e.g. the Living Standards Measurement Surveys (LSMS) that begun in 1980 (Deaton and Zaidi, 2002) and are still carried out. The surveys may include information related to energy end-uses e.g. the quantity of fuels and electricity used in the household, or the behaviour of end-users in relation to energy. Data extracted from these surveys can be used to build a picture of household energy use, the types and efficiency of end-use devices, and the services delivered.

Table 2.2 summarises research approaches, topics and the intended scope, of several studies which make use of data collected in developing countries for household surveys.

These studies explore a range of themes related to household energy use, living conditions and well-being of the occupants. Household surveys are typically undertaken by researchers or country-based statistical bodies, the latter tend to include panel surveys. Researchers have explored household characteristics and their influence on: energy use, appliance use, the affordability of devices, electricity provision, household practices and urbanisation. Income is found to have a dominant influence on the type and number of end-use energy devices owned, and the energy sources selected in households. However, the studies reveal that adoption rates of more efficient end-use devices still vary widely across income groups. For example, the use of traditional biomass for cooking, particularly charcoal, remains stubbornly prevalent in some countries- even for wealthier households- whereas, modern lighting devices have been adopted almost uniformly across income groups (Rahut, Behera, Ali and Marenya, 2017*a*; Choumert-Nkolo et al., 2019). The settlement type, either rural or urban, is a driver of the type of energy sources used (Sohail et al., 2017), with increased population density in cities making electrification and natural gas use more prevalent (Choumert-Nkolo et al., 2019; Debnath et al., 2019). Table 2.2 also reveals that few studies use household surveys to explore useful energy, the efficiency of end-use devices, or the provision of services.

Table 2.2 Comparison of studies that use surveys.

					Energy scope		*Non-energy scope*		
Author	*Method*	*Data*	*Location*	*Several energy sources*	*Services*	*Final E^b*	Socioec. char.	*Outcomes studied*	*Conclusions*
Rahut, Behera, Ali and Marenya (2017*a*)	Survey and multinomial logit and ordered probit econometric models	LSMS	Ethiopia, Tanzania, Malawi, Uganda	N (only electricity)	N	Y	Y	Wealth, education, income status	Rural households are less likely to adopt electricity for light and light and cooking. Wealthier households tend to be connected to the grid. Access to infrastructure, wealth status, convenience of use and household head education are significant determinants of household use of electricity for cooking and lighting.
Rahut, Behera and Ali (2017)	Survey and multinomial logit and ordered probit econometric models	Living Standards Measurement Survey (LSMS)	Ethiopia, Tanzania, Malawi	Y	Y (only lighting)	Y	Y	Wealth, income status	The education level of the household head impacts the type of energy source used for lighting, a higher level tends to use more electricity and solar lighting. Similar effects were found for wealth, income status, as well as infrastructure and location
de la Rue du Can et al. (2019)	Scenario-based modelling for India's economy	Surveys and LEAP model	India	Y	Y (considered, but not explicitly quantified)	Y	Y[a]	CO_2 emissions, final energy by sector	India can achieve its NDC targets with current policies. Opportunities lie in commercial buildings and main materials sectors.
Choumert-Nkolo et al. (2019)	Survey and multinomial logit based on fuel stacking techniques	LSMS and Nighttime Lights Data	Tanzania	Y	Y (cooking and lighting)	N	Y	Expenditure, women's bargaining power, wealth	As household incomes rise, a wider variety of fuels is used. The choice of fuels for lighting and cooking are not dependant on each other. Charcoal is adopted as people transition away from firewood and animal residue. Modern lighting fuels are adopted faster.
Sohail et al. (2017)	Multivariate regressions	National Human Development Survey	India	Y (as expenditure)	Y (transport)	N	Y	Public health and climate change	They concluded that urbanisation and household infrastructure (including modern cooking and clean water) can reduce short-term morbidity
Lenz et al. (2017)	Differences-in-differences approach	Surveys	Rwanda	Y	Y (lighting and others as device ownership)	N	Y	Income, education, health	The effects of electricity access have an impact on the use of lighting (alongside a reduction of 1.3 L/month of kerosene usage) while appliances are used more (radios, TV sets and electric irons), and new beneficial connection-sharing dynamics with neighbouring households were observed.
Bisaga and Parikh (2018)	Surveys	Survey	Rwanda	N	Y (lighting, other appliances, cooking)	N	Y	Time of use, motivation for ownership, social practices	The adoption of solar home-systems (SHS) enables mainly the activities of lighting and phone charging and some households may 'downgrade' from having access to the grid to adopt SHS due to the grid's unreliability and power surges.
Rao and Ummel (2017)	Penetration curves	National surveys paired up with other datasets	India, South Africa and Brazil	N (only electricity)	Y (appliance-related: TV, mobile phone, refrigerator, washing machine)	N	Y	Appliance ownership, wealth, national differences	Income is still the predominant driver of aggregate penetration levels. Income alone is insufficient to explain the differences in appliance ownership which was impacted more by wealth, culture and other household characteristics, particularly in low-income households.
Debnath et al. (2019)	Structural Equation Modelling	Survey and social practice theory	India	N (only electricity)	Y (appliance-related)	N	Y	Time performing activities, appliance characteristics	The transition to urban slums triggers energy-intensive indoor living, based on the ownership of more appliances, due to the isolation of activities and space-bounding of the residents.

[a] Mostly separating by urban and rural.

[b] Only final energy is included on the table, because no further transformations to useful energy or services are included in the studies.

Summary from section 2.2

Demand-side options, which are closer to services, have the potential to reduce energy use and emissions. The quantification of energy conversion up to useful energy or exergy is hindered by the lack of data with enough granularity on conversion devices, the lack of standardised methodologies applied at an international scale and the lack of uncertainty estimations. The problem of data scarcity is exacerbated in developing countries.

Exploring options for service provision will also provide increased human well-being, while limiting environmental impacts, thereby offering a way to comply with NDC. To ensure such service provision options and other resulting energy transition pathways are coherent and actionable, local stakeholders should be involved in the process of creating and informing models.

In the case of country-level studies for developing countries, the lack of reliable conversion device data and final energy data hinder service provision analyses. Data that is nationally representative is also required to make country-level models. Nationally-representative household surveys show potential for developing countries to increase their quantification of services. With limited time for climate action, there is a gap to identify whether information gathered in country household surveys may be harnessed to better quantify useful energy and service delivery to propose actions to lower emissions.

2.3 Policies surrounding the resource chain

The challenges of both increasing service provision in developing countries, and switching to low-carbon systems in developed countries, while simultaneously constraining emissions cannot be underestimated. Anadon et al. (2016) suggest that tackling these challenges will require the involvement of several actors and institutions, systematic learning from past efforts, technical innovation from incubation to diffusion and institutional shaping of innovation. Policy reforms are key to facilitate the necessary changes, given their contribution to creating an environment where change can occur. However, integrating new policies into the existing policy space is complicated, given the propensity for stakeholders to push for new policies in different directions, e.g. the recent proposal of the EU president to increase the 2030 target for emission reduction to at least 55 % admitting that “this increase from 40 to 55 [%] is too much for some, and not enough for others" (EU, 2020).

Some countries encourage academics from several disciplines to know and inform policy-making processes, e.g. the collaboration between UK Parliament or other UK legislatures and researchers for higher impact (UK Parliament, 2020). These collaborations are particularly relevant for the Paris Agreement, since systemic changes need to occur within specified timelines. Research around service provision could then reveal additional policy leverage points for reducing GHG emissions and increasing well-being.

2.3.1 Policy making for the energy transition

Public policy is a “purposive course of government action or inaction that responds to public problems" (Kraft and Furlong, 2018) e.g. approving regulations, spending money, or providing tax breaks, which has direct and indirect impacts on the population. Formal actions that governments take to pursue their goals are known as policy outputs, and the effects of those actions are known as policy outcomes (Kraft and Furlong, 2018).

Policies have goals that use a combination of actions can be used to enact them, such actions are called *policy instruments*. There are several instrument classifications described in the literature. An early policy typology by Lowi (1972) which identifies distributive, re-distributive, and regulatory policies (which include regulation of business i.e. competitive regulation, and of protection of the general public, i.e. protective regulation). The International Energy Agency (IEA) classifies polices into nine different categories: Education and Outreach, Financial instruments, Incentives and Subsidies, Public Investments, Research, Development and Distribution (RD & D), Regulatory Instruments, Tradable Permits, Voluntary Agreements, and Framework Policy. Whereas Kern et al. (2017) describes three broader areas: economic (subsidy, loans, taxation, public procurement, Research and Development (R&D)), regulatory (regulation) and soft (voluntary measures and information). More recently, the IRENA et al. (2018) proposed an updated classification of policy instruments for energy transitions. Their proposal acknowledges that a mix of instruments is used and thus classifies policies as: direct (push i.e. mandating actions; pull i.e. incentivising actions; and fiscal/financial), integrating (which consider specific end-uses and the broader energy and economic systems), enabling (which include policies in the wider contexts of the transition e.g. financing, carbon pricing, the labour market). A mix of integrating and enabling instruments is also identified (to include governance and institutions, behavioural change, social protection, among others) (IRENA et al., 2018).

Policy making is constantly occurring, leading policies to co-exist, so new and existing policies may have common dynamics. Such dynamics should be considered when creating amendments and new policies. Processes to design and update policies include *policy packaging* and *policy patching*, the former referring to the creation of new measures to replace the existing ones and the latter to the addition of measures to complement existing ones (Howlett and Rayner, 2013). Kern et al. (2017) have argued that to achieve a coherent and consistent policy mix, “strategic policy patching may be a more promising approach for policymakers than the creation of completely new policy packages."

Transitioning between energy systems requires a mix of policies, which can address the influence of different actors, investment risks, bottlenecks, failures or system characteristics that require changing (Schmidt and Sewerin, 2019). However, the success of policy mixes is restricted by the nature of policy processes (Rogge and Reichardt, 2016). The World Bank and ESMAP (2018) also stresses that well-functioning institutions are essential for successful policy enforcement, while Geels et al. (2016) suggest additional criteria to select policies for implementation, which are: cost-effectiveness, socio-political feasibility, social acceptance and legitimacy, and flexibility. These criteria impact how policies for the energy transition occur, e.g. the decreasing gap in risk perceptions between the public and experts on climate change in the US (Sullivan and White, 2019), or the implementation of regulatory instruments such as feed-in tariffs for solar photo-voltaic (PV) adoption that were replaced once cost-effectiveness was achieved (IRENA et al., 2018). Janoska (2017) also warns that any recommended solution to increase the speed of energy transitions in any country will need to consider making policy packages for short- and long-term actions within specific country contexts.

The policy research discussed previously has shown that regulating the energy transition requires a mix of policies, well-functioning institutions, favourable policy environments, and a re-structuring of policy instruments. The creation of policies also needs to occur hand-in-hand with technology innovation stages, favouring policy-patching over time, and the use of apt instruments for the policy goals. Finally, short- and long-term actions as well as the different country contexts need to be considered.

2.3.2 Direction of current energy policy research and its relevance for development

Policies for energy transitions can be divided into the sectors involved and the type of policies created. Policies for energy transitions were first rolled out for primary energy, specifically power generation, with the integration of renewable energy generation in the power infrastructure and markets (IRENA et al., 2018). The IEA (2019*b*) classifies Other energy efficiency policies into three different sectors: transport, with the setting of fuel economy standards; buildings, with the regulation of their minimum energy performance including heating, cooling, water heating and appliances; and industry, where energy-intensive industries and motor-driven systems are regulated. The EU in particular has regulated these sectors under the Energy Efficiency Directive set in 2012 (European Union, 2012), with Bosseboeuf (2015) observing an overall efficiency increase of 15% in the EU between 2000 and 2013. The IRENA et al. (2018, Chapter 1) identify that between 2014 and 2016, the number of global renewable energy policies mainly referred to the power sector, with 126 countries having such policies in place in 2016. The transport sector followed with 68 countries with policies in place in 2016, while heating and cooling policies were only available in up to 29 countries in 2016, with only 21 being related to renewable energy. The IEA (2020*b*) attribute an energy demand reduction to technical gains in energy efficiency since 2000, however they note that there has been a slowdown in such gains in the services and residential sectors related to the relaxation of energy efficiency policies.

Policies on renewable energy generation first used the instruments of feed-in-tariffs and premiums, which have been followed by tendering and net-metering (IRENA et al., 2018). Feed-in tariffs are prices set for electricity generated using renewable sources, while premiums are paid on top of electricity prices to the generator. Carley et al. (2017) conclude that feed-in-tariffs and renewable portfolio standards are predictors of renewable energy market growth. These instruments enabled technologies under development (i.e. wind and solar) to scale up while their prices became competitive.

Pollitt (2012) remarks that the global energy liberalisation (which includes energy generation privatisation, monopoly regulation, and improved competition mostly for energy generation) started in the 1980's and marks the start of the energy transition. The liberalisation of energy led to modest efficiency gains globally. However, Pollitt remarks that households in many countries had no direct benefits from such energy liberalisation. Further, Carley et al. (2017) warn that regulating energy generation by increasing the share of renewable energy does not necessarily decrease reliance on fossil fuels.

The policies on renewable energy generation rely on the regulation of technology diffusion in the policy mix, leading Schmidt and Sewerin (2019) to propose a policy mix balance, i.e. a balance of strengths and weaknesses of the policies in place, from conceptualisation to measurement, that considers the intensity and technology specificity in policy design. Schmidt and Sewerin were able to observe how technology diffusion in nine OECD countries varied across renewable energy technologies from 1998 to 2014. Their hypothesis was that a policy mix with a more balanced combination of instrument types would be more conducive to inducing socio-technical transitions than an unbalanced combination. Schmidt and Sewerin observe that the policy mix in each country has varied dynamics, with technology specificity showing notable differences, while the policy balance varies less. Despite the use of novel balances, there are opportunities to apply them to more countries and other aspects of service provision beyond renewable energy generation, e.g. energy efficiency or service provision.

Other policy studies use a technology perspective beyond a single use of a technology, e.g. renewable energy generation, and, instead, consider either multiple applications (Schmidt et al., 2016) or multiple technologies at different stages of the resource chain Bosetti et al.

(2015). Schmidt et al. (2016) investigate the potential technology lock-in of considering multiple applications of a single technology. They select four stationary battery technologies used in energy system applications such as smoothing the operation of the electricity generation for both renewable and fossil fuel sources, as well as in transmission and distribution, and industrial or private consumers who have high power requirements or need storage for self-consumption. Schmidt et al. conclude that policy makers are faced with choosing certain technologies and applications when they regulate technology diversity, and advise that experts in different applications need to be consulted. Bosetti et al. (2015) assess energy technology costs from expert elicitation surveys for a mix of key technologies used at different stages of the resource chain, particularly power generation, transport and Carbon Capture and Storage (CCS). The technologies include solar, nuclear, biofuels and bio-electricity, and CCS. Bosetti et al. (2015) observe that the costs of nuclear energy dominates the other technologies. They also note that improving the performance of a single technology can make the energy system react unexpectedly, given the complexity of the interactions of the policy mix. These studies highlight the complexity of designing policies for the energy transition, but also show that previous theories and methods in policy research can be applied to a broader range of technological applications.

Academics and institutions such as the World Bank and ESMAP recognise that energy transitions will require a more systematic approach and a focus beyond renewable energy generation. The more systematic approach is exemplified by Rogge et al. (2020), who use the concept of ‘socio-technical transitions’ in renewable energy generation research, which refers to decarbonisation pathways that consider economic, political and social bottlenecks. The analysis by Rogge et al. focuses on the increased use of renewable energy generation and the socio-technical change involving institutional change, strategic planning and communication, including different actors. The focus beyond renewable energy generation is highlighted by the World Bank and ESMAP (2018), who argue that clean energy policies focus strongly on electricity, with the heating and transportation sectors often being overlooked. The IEA (2020*b*) further highlights that most technology improvements in energy transitions have focused on the supply side, yet few technological breakthroughs have occurred in the demand-side. Meanwhile, Grubler et al. (2012) also highlight the need to rebalance policies and public expenditure in innovation to include demand-side technologies. Wilson et al. (2012) further note that policy coverage of primary energy is preferred over policies promoting efficient end-use technologies, despite the large emission reduction potential with higher social returns on investment of end-use technologies compared to energy-supply ones. IRENA et al. (2018) have then made efforts to divide policies into sectors and identify some end-uses, such as heating, cooling and cooking, identifying vast opportunities in the heating and cooling sector, as it is the largest end-use sector. The examples discussed highlight that, as research focuses more on end-uses and systematic approaches, the integration of service provision into policy research could be feasible.

Policies to reduce energy demand in the transport sector stimulate the development and commercialisation of technologies, fuel efficiency and emissions standards (IEA, 2020*b*). Transport policies in the EU focus mainly on passenger transport, with 70% of all measures for this type, while freight transport is addressed by the remaining 30% of the policies (Bosseboeuf, 2015). Overall, efficiency gains in the passenger transport sector have been partially offset by a shift to larger vehicles (IEA, 2020*b*). Craglia and Cullen (2019) argue that fuel standards had little effect on technical efficiency improvements in the UK because some manufacturers have met emissions standards by “increasing the divergence between laboratory tests and real-world fuel consumption". Going forward, Craglia and Cullen (2020) suggest that future efforts in emissions reductions require policies that focus on vehicle electrification, size and power, as they account for 80% of the uncertainty in future emissions. For freight transport, Bosseboeuf (2015) discuss that the energy efficiency progress for trucks in the EU stopped since 2007 due to less efficient operations in terms of reduced load factors. In a global study, Paoli (2019) advises that creating power-train-specific fuel economy standards, and extending fuel economy standards for freight will aid in achieving energy efficiency potentials.

Policies in the sector of buildings involve several aspects, from building standards, to regulation of the efficiency of appliances and end-uses such as heating and cooling in both the commercial and residential sectors. The (IRENA et al., 2018) identify that policies for the inclusion of renewable energy sources for heating and cooling are lagging behind primary energy and transport policies, with most of the policies that include heating and cooling being located in the EU. Bosseboeuf (2015) identifies that EU measures in the buildings sector has resulted in a higher uptake of heat pumps and solar PV, and efficiency improvements of 1.8% between 2000 and 2012 in households due to more efficient appliances and space heating. In turn, developing countries have focused on phasing out of biomass use for cooking, while emerging economies are creating policies for solar water heating or biogas for heating e.g. Brazil (IRENA et al., 2018). In a global quantification, Paoli (2019) argues that coolers and heat pumps show potential for emission reductions, however their deployment requires policy instruments, such as minimum energy performance standards and publicly-funded R&D to achieve potential savings through these and other innovations.

The contrasting conditions between developing and developed countries, illustrated by the research discussed, are due, in some important part, to the varied levels of access to electricity, which has an effect on their policy aims. Developed countries enjoying high levels of electricity access, while developing ones have intermittent or low access (IEA, 2019*a*). Thus, the energy policies in place have different priorities. IRENA et al. (2018) discuss that developing and emerging countries have set up policies and targets to increase electricity access, including the use of renewable sources, in distributed generation (e.g. mini-grids) and in the off-grid sector, while other policies aim to increase the quality of products, especially off-grid solar ones. The IEA (2019*a*) identifies that the targets set by the African Union in Agenda 2063 (African Union Commission, 2020) (which is the economic and industrial development vision for the region which has 55 members) will not be enough to achieve their targets of electricity access and clean cooking for the whole population in the region. Furthermore, the IEA (2020*b*) acknowledges that, with energy-intensive industries moving out of developed countries, any emission reduction targets in those sectors depend on the countries where those industries are. However, these countries tend to have less stringent emission policies.

The research discussed so far demonstrates the stark contrasts in policy aims for different sectors that depend on country development levels. The research showed that energy transitions have been focused mainly on primary energy in developed countries, with some additional measures for transport, building efficiency and industrial measures. In turn, developing and emerging countries focus on some of those same measures, but also include general energy and electrification access, and changes in practices such as cooking, or the use of local resources to generate alternative primary energy sources such as biofuels. However, in general, further policy development is still required to address the needs of energy transitions or climate-compatible development, since some sectors have been overlooked, and trade dynamics need to be considered to regulate global emissions.

The policies energy transitions are widely linked to innovation e.g. solar PV or wind have undergone several technology development stages to reach maturity and widespread diffusion. Thus, aiming to reach a more systematic understanding of innovation, Grubler et al. (2012) characterise policy efforts in innovation. They conclude that policies need to be complementary to existing ones and to think in terms of systems to achieve proposed changes. Grubler et al. also highlight that critical innovations will require the consideration of local conditions for energy supply, as well as specific end-uses. To challenge current systems, Wilson et al. (2019) explore 99 potential innovations at various points of the resource chain (including innovations in transport, sustenance, buildings, to electricity systems), which are found to offer emissions reductions opportunities. Policy makers must be prepared to meet certain challenges related to innovation systems, which Anadon et al. (2016) suggest should include learning mechanisms, the inclusion of interests of underserved people, and reformed institutions so sustainable development is achieved. Thus, policies that address both energy transitions and climate-compatible development need to include support for alternative innovations that can reduce emissions and change systems, by creating policy environments where such innovations may be allowed to develop and be taken up.

The research discussed has shown that there is some hope in advancing the understanding of policy making processes to accommodate energy transitions with a more holistic approach, considering technologies closer to services and the systemic change needed. The studies show that there is an opportunity to take advantage of previous academic work on energy transitions and apply this to end-uses and service provision, including innovation that enables changes that benefit countries at different development levels.

Summary from section 2.3

The energy transitions have incited work on policy making processes, providing useful insights around the conditions that enable such transitions. Researchers have shown that energy transitions require a policy mix that focuses on policy patching, instruments adequate for the policy aims, which can be modified depending on policy needs and innovations, and a favourable policy environment. So far, these insights have been mainly focused on primary energy and the influence of renewable energy sources. Thus, there is a gap to include other parts of the resource chain in energy policy research.

A smaller group of researchers is moving closer to considering end-uses and systemic change, since many academics and institutions have recognised the opportunities for reducing emissions in such areas, the potential innovations at other parts of the resource chain, and the additional socio-economic systems that require changing alongside energy. The new focus shows that there is an opportunity to apply past policy research and methods in such new aspects of the energy transition, as well as to include service provision.

The consideration of local contexts is a key area of focus for energy transitions to occur and to bring climate-compatible development, given the different policy aims depending on the level of country development. Thus, unless policy making insights are conveyed between countries at varying degrees of development to increase the chances of success in achieving the transition under the current pressing circumstances, there are higher chances of locking in high carbon systems or insufficient levels of development.

2.4 Statement of the research questions

This thesis investigates the insights that may be gained by analysing service provision for enhancing human well-being, while emissions are reduced. The first step to generate such insights is to determine the steps followed by resource transformations, and identify available indicators to trace such transformations in different countries. Such indicators and their link to well-being can then be explored. The literature reviewed in section 2.1 showed there have been advances in understanding the links between some parts of the resource chain, emissions and some well-being indicators, showing strong correlations at varying degrees and levels of coupling over time. Despite the efforts, there are three main drawbacks. First, the lack of a systematic study considering the different stages in service provision and well-being. Second, the lack of a standardised terminology given the many academic disciplines involved. These two drawbacks hinder research efforts, leading to only partial conclusions to be drawn. The third drawback is the scarcity of granular data to quantify the resource chain, mainly for developing countries. These research gaps are then explored in Chapter 3 to answer the question: '*To what extent have increases in services delivered been associated with higher levels of development?*'

The literature in section 2.2 showed that demand-side options have a high potential to reduce emissions and are closer to services. However, some limitations to understand demand-side options and service provision are the lack of reliable data on energy end-uses, the lack of a standardised methodology and the few uncertainty estimations. The limitations seem to be predominant in developing countries, where achieving climate-compatible development is key. Nationally-representative household surveys show potential to be employed to quantify service provision in developing countries. Apart from quantitative methods to identify interventions, the literature showed that the involvement of local stakeholders to propose changes to service provision is crucial. These research gaps are explored in Chapter 4 to answer the question: '*What insights on local service delivery may be drawn from harnessing available developing country data?*' This question will be answered including insights from local stakeholders.

Technical insights on resource transformations in countries to deliver services are important to answer the overall research question of this thesis. However, the role of policies is fundamental to facilitate both the energy transition and climate-compatible development. Section 2.3, has discussed research advances on effective policies for regulating the energy transition. Most policy research is shown to focus on energy generation, highlighting the importance of well-balanced policy mixes and an adequate policy environment. Some advances have been made to include policies closer to end-uses and more holistic approaches including socio-economic system changes. Then, there is an opportunity to use previous policy research insights in stages closer to services. Such insights include the analysis of policy balances, since they have only included developed countries and instruments that regulate renewable energy generation, but not other countries or characteristics. The inclusion of services or resource transformations in policy research is further hindered by the scarce analyses of energy policies in developing countries, despite the urgent need for climate-compatible development. This thesis aims to identify the stages of the resource chain in global policy research for the first time to give further insights on service provision regulation. These research gaps are then explored in Chapter 5 to answer the question: '*Where along the resource chains are energy policies focused both historically and at different country development levels?*'

The research questions will be investigated in Chapters 3-5, and are shown again below:

RQ 0 What insights about human well-being and emissions reduction can be gained by exploring and quantifying service provision?

RQ 1 To what extent have increases in services delivered been associated with higher levels of development?

RQ 2 What insights on local service delivery may be drawn from harnessing available developing country data?

RQ 3 Where along the resource chains are energy policies focused both historically and at different country development levels?

3

Global energy services and development

3.1 Introduction

Chapter 2 presented the advances in research around parts of the resource chain, such as energy and material stocks, flows and transformations, and their linkages to broader social and environmental outcomes. The studies showed strong correlations between parts of the resource chain with development and well-being, obtaining varying levels of coupling between the indicators over time. Despite the advances in linking some part of the resource chain and some well-being measures, and the progress in developing theoretical frameworks around services, quantifying the systematic frameworks from resource transformations to well-being has scarcely been done. The lack of quantification of such transformations is due to the different variables to consider, the different terminology used, and the data scarcity in many developing countries.

To address the gaps in the literature, this chapter presents an analytical framework to quantify resource transformations and their interactions, including environmental and well-being or development outcomes. This is the first time these interactions are studied in a systematic way. The interactions are studied by identifying indicators for service provision and development. Regressions are undertaken between pairs of service provision and development indicators in recent years to determine whether increases in service delivery have been associated to higher development. The resource chain proposed in the previous section is considered in the regressions, since service provision indicators at different points of the resource chain are identified. This chapter will focus on both developed and developing countries to compare resource transformations and outcomes. The results may help identify opportunities to improve development outcomes, set benchmarks on service provision and better understand social and environmental effects.

Figure 3.1 shows the relevant stages of the resource chain and the research question of this chapter.

RQ1: *To what extent have increases in services delivered been associated with higher levels of development?*

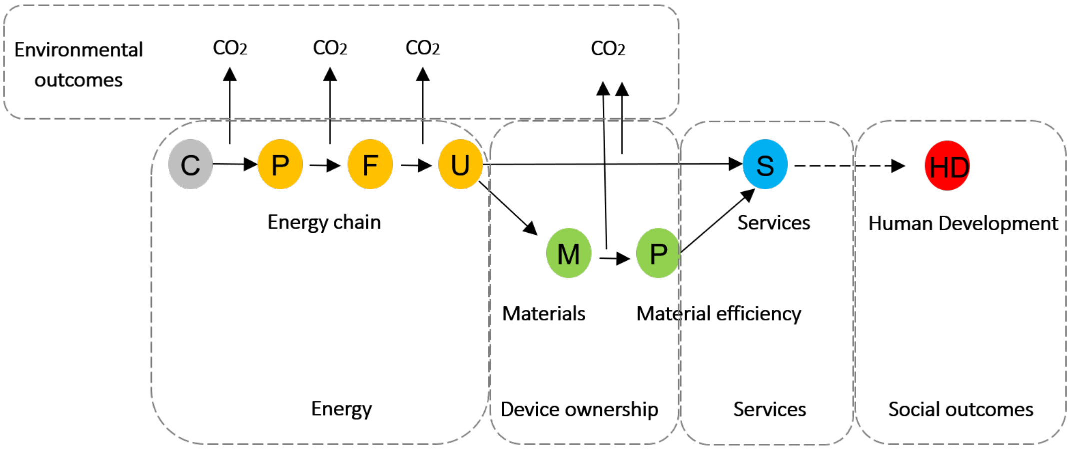

Fig. 3.1 Resource chain to provide services and the parts considered in this chapter. The dashed boxes refer indicators of resource chain parts, such as the energy chain, device ownership, built stock, services, and social and environmental outcomes.

This chapter is structured as follows: Section 3.2 presents the data gathered for this study and the methods used to analyse such data. Section 3.3 contains the results. Section 3.4 discusses the results, and makes comparisons with the literature. Finally, section 3.5 summarises findings and discusses policy implications.

3.2 Data and Methods

This study compares regression results between final energy, device ownership, built stocks, social and environmental outcomes associated with services, as well as total primary energy and total embodied emissions with several development indicators. Different indicators were identified and obtained for such purpose, which will be detailed in section 3.2.1, along with the methods used, including the form of the regression as shown in section 3.2.3. The limitations of the methods are discussed in section 3.2.4.

3.2.1 Service provision and development indicators

Service provision data used in this study is available from several international organisations with indicators ranging from energy use to social and environmental outcomes. Even though international organisations are used because their databases are reliable, data availability varies from country to country, as well as the methods and indicators of the organisations collecting the data. The references for the indicators used in this study are shown in table 3.1. It is important to note that the environmental impact is quantified as CO_2 emissions which are related to domestic final demand (C_{emb}), which is close to services. More information about this type of emissions can be found in appendix A. The emissions are presented by source country and industry and so the relevant sectors/industries per service are used in the analysis.

As development indicators, HDI, IHDI and their related components for health, education and income are used, which are shown in table 3.2. Those development indicators are chosen as the dependent variables, because they make the results comparable to literature in the field and because HDI has been used to represent development of different countries for several years, and was updated to account for inequality, thus making the database extensive enough for this study's purposes.

This analysis considers data for between 11 and 213 countries depending on the indicator, with OECD countries having the highest representation, and ranging from one to 57 years of tracking the same indicator between the years of 1870 to 2018, totalling around 96,000 data points.

Table 3.1 Services and surrounding indicators considered in the study.

Activity	*Resource chain*	Indicator (unit)	Reference
Passenger Transport	Final energy	Total passenger transport (GJ/cap)	IEA (2017)
	Device ownership	Road vehicles (units per 1M people)	Ritchie and Roser (2020)
	Social or environmental outcome	CO_2 emissions per cap (emb in FD)[b]	OECD (2019)
	Service	Total passenger km (10^3 pass-km/cap)	IEA (2017)
Freight Transport	Final energy	Total freight transport (GJ/cap)	IEA (2017)
	Social or environmental outcome	CO_2 emissions per cap (emb in FD)[b]	OECD (2019)
	Service	Total tonne km (10^3 tkm/cap)	IEA (2017)
Thermal comfort	Final energy	Residential space cooling (GJ/cap)	IEA (2017)
		Residential space heating (GJ/cap)	
		Services space cooling (GJ/cap)[a]	
		Services space heating (GJ/cap)	
	Built stocks[c]	Built area (km^2/cap)	
	Social or environmental outcome	CO_2 emissions per cap (emb in FD)[b]	OECD (2019)
Communication	Final energy	Televisions (GJ/cap)	IEA (2017)
		Personal computers (GJ/cap)	
	Device ownership	Mobile phone ownership (units per 1000 people)	Ritchie and Roser (2020)
		Fixed telephone subscriptions (subs per 1,000 people)	World Bank (2019)
	Social or environmental outcome	CO_2 emissions per cap (emb in FD)[b]	OECD (2019)
Sustenance	Final energy	Residential cooking (GJ/cap)	IEA (2017)
		Refrigerators (GJ/cap)	
		Freezers (GJ/cap)	
		Refrigerator/Freezer combinations (GJ/cap)	
	Social or environmental outcome	Prevalence of obesity in the adult population	FAO (2020)
		(>=18 years) (%)	FAO (2020)
		CO_2 emissions per cap (emb in FD)[b]	OECD (2019)
	Service	Food supply (kcal/cap/day)	FAO (2020)
		Fat supply quantity (g/capita/day)	
		Protein supply quantity (g/capita/day)	
Health	Device ownership	Hospital beds (beds per 10,000 cap)	WHO (2020)
		Medical doctors (docs per 1,000 cap)	
	Social or environmental outcome	Births attended by skilled health personnel (%)	
		CO_2 emissions per cap (emb in FD)[b]	OECD (2019)
Other	Social or environmental outcome	Total CO_2 emissions per cap (emb in FD)[b]	OECD (2019)
	Primary energy	Total primary energy use (MJ/cap)[d]	World Bank (2020*b*)

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[a] *Services space cooling and heating* refers to the sector, which differs from the service concept that is the main thesis topic.

[b] FD refers to final demand. The term 'embodied' in this case is different from the CO_2 embodied in materials that is commonly used in civil engineering. Specific emission indicators by service are shown in table 3.3.

[c] Building stocks are only included in thermal comfort given the fact that thermal comfort is commonly modified within the confined space of a building.

[d] Defined by the World Bank (2020*b*) as the "use of primary energy before transformation to other end-use fuels, which is equal to indigenous production plus imports and stock changes, minus exports and fuels supplied to ships and aircraft engaged in international transport."

Table 3.2 Development indicators considered in the study.

Development Indicator (unit)	*Short name*	*Reference*
Average total years of schooling for adult population (years)	AvYSch	UNDP (2020*b*) Roser (2020)
Expected Years of Schooling (years)	EYSch	UNDP (2020*b*) Roser (2020)
GNI per capita, PPP (constant 2011 international $) (Rate)	GNI	UNDP (2020*b*) Roser (2020)
Inequality-adjusted Human Development Index	IHDI	UNDP (2020*b*) Roser (2020)
Life expectancy at birth, total (years)	LExB	UNDP (2020*b*) Zijdeman and Ribeira da Silva (2015) Riley (2005) Roser (2020)

3.2.2 Summary statistics

Table 3.3 shows the indicators used per category, the locations covered and a summary of the values of the indicators and transformed units. Such units allow for values to have similar ranges for ease of comparison.

The information available per indicator is varied. The Sustenance indicators related to final energy of freezers and refrigerators consider only three continents, followed by the emissions related to personal computers, final energy of Residential Space Cooling and refrigerator/freezer combinations which consider only four continents. Similarly, the number of countries in scope is low for final energy of refrigerators ($n_{countries} = 5$), emissions of personal computers and final energy of Residential Space Cooling (both $n_{countries} = 11$).

Table 3.3 Data summary

Category	*Indicator (Ind)*	*Unit*	*Country n*	*Continent n*	*Year n*	*Year min*	*Year max*	*Ind mean*	*Ind min*[a]	*Ind max*
Passenger Transport	Passenger-kilometres	10^3 pkm/cap	31	5	17	2000	2016	12.73	3.25	28.19
	Road vehicles	vehic/10Kcap	189	5	1	2014	2014	21.39	0.1	89.9
	Total passenger transport	GJ/cap	27	5	17	2000	2016	20.3	0.02	68.79
Freight Transport	Motor vehicles, trailers and semi-trailers	kg CO_2/Mcap	62	5	7	2005	2015	0.7	0	3.97
	Tonne-kilometres	10^3 tkm/cap	31	5	17	2000	2016	7.44	1.63	32.08
	Total freight transport	GJ/cap	27	5	17	2000	2016	11.15	0.43	32.59
Resid. thermal comfort	Residential space cooling	GJ/cap	11	4	17	2000	2016	0.53	0.02	3.14
	Residential space heating	GJ/cap	30	5	17	2000	2016	15.29	0.12	31.8
Services thermal comfort	Services space cooling	10MJ/cap	15	5	17	2000	2016	110.08	2.94	410
	Services space heating	10MJ/cap	18	5	17	2000	2016	655.85	2.94	1712.9
Thermal comfort	Built space	km^2/cap	186	5	3	1990	2014	124.11	0.15	546.29
	Utilities[c]	kg CO_2/Mcap	63	5	7	2005	2015	71.47	0.21	641.79
Communication	Computer, electronic and optical products	kg $CO_2/10^5$cap	63	5	7	2005	2015	11.92	0.06	84.79
	Fixed telephone subscriptions	per 100 people	212	5	46	1960	2017	16.14	0	132.72
	IT and other information services	kg $CO_2/10^5$cap	62	5	7	2005	2015	4.13	0	34.77
	Mobile cellular subscriptions	per 100 people	213	5	38	1980	2017	50.73	0	321.8
	Personal computers	10MJ/cap	11	4	17	2000	2016	28.26	4.26	71.62
	Publishing, audiovisual and broadcasting acts	kg $CO_2/10^5$cap	61	5	7	2005	2015	1.6	0.02	12
	Telecommunications	kg $CO_2/10^5$cap	61	5	7	2005	2015	3.05	0.05	30
	Televisions	10MJ/cap	19	5	17	2000	2016	44.11	10	122.22
Sustenance	Domestic households	kg CO_2/Mcap	62	5	7	2005	2015	1.98	0	24.39
	Fat supply quantity	g/cap/day	171	5	4	2014	2017	87.66	22.46	167.64
	Food products, beverages and tobacco	kg CO_2/Mcap	63	5	7	2005	2015	2.7	0.02	15.94
	Food supply	kcal/100cap/day	171	5	4	2014	2017	28.52	17.55	38.45
	Freezer	10MJ/cap	17	3	17	2000	2016	33.13	9.09	80
	Prevalence of obesity in the adult population	%	190	5	17	2000	2016	16.23	0.6	60.7
	Protein supply quantity	g/cap/day	171	5	4	2014	2017	81.26	37.95	141.01
	Refrigerator/Freezer combinations	10MJ/cap	19	4	17	2000	2016	62.87	9.09	161.05
	Refrigerators	10MJ/cap	5	3	17	2000	2016	26.3	6.25	50
	Residential cooking	100MJ/cap	29	5	17	2000	2016	13.5	3.33	56
Health	Births attended by skilled health personnel	%	184	5	20	2000	2019	92.05	5.7	100
	Hospital beds	beds/10Kcap	180	5	16	2000	2015	39.29	1	143
	Human health and social work	kg $CO_2/10^5$cap	62	5	7	2005	2015	1.94	0.03	33.33
	Medical doctors	doctors/10Kcap	191	5	29	1990	2018	20.75	0.13	84.22
Primary energy	Total primary energy	MJ/cap	171	5	56	1960	2015	98974.92	1815.4	1704451
Emissions	Total emissions	kg/cap	64	5	11	2005	2015	8.11	0.35	26.34
Development ind	AvYSch	years	192	5	52	1870	2017	5.48	0.01	14.1
	EYSch	years	192	5	28	1990	2017	11.75	2.1	23.3
	GNI	Rate	189	5	28	1990	2017	16349.89	332.27	119118.4
	HDI	NA[b]	188	5	29	1990	2018	0.66	0.19	0.95
	IHDI	NA[b]	164	5	9	2010	2018	0.56	0.2	0.9
	LExB	years	207	6	57	1960	2016	63.88	18.91	85.42

[a] All the values used are positive ones, so any zeros are due to rounding.

[b] NA: Non applicable as it is an index.

[c] Utilities refers to emissions classified as: Electricity, gas, water supply, sewerage, waste and remediation services.

3.2.3 Regression analysis

The nature and form of the relationship between the service and development indicators are studied using Ordinary-Least Square (OLS) regressions, where a separate regression is run for each pair of service and development indicators. The service indicators used in the regressions are normalised so their values are in the range of zero to 100, which allows for direct comparisons of the curves. The service and development indicators are used as independent and dependent variables respectively. A semi-logarithmic least square fit is commonly employed in the literature when analysing the relation between some form of energy and HDI (e.g. (Arto et al., 2016)), given the non-linearity of the data. This approach in the literature has guided the form of the regressions in this chapter, as shown in equation 3.1, where y is the development indicator, a is the intercept, and b is the coefficient corresponding to the independent variable corresponding to the service indicator studied x, and ε is the error term. Heteroskedastic robust standard errors were used, using the HC3 estimator based on Mackinnon and White (1985), available in Python's statsmodels OLS. Consult appendix A for more information on the errors.

$$y = a + b\,log(x) + \varepsilon \tag{3.1}$$

The data for the indicators used in the regressions are also checked for outliers, where the values for North Korea and Curacao get removed for the indicators of hospital beds and total primary energy respectively.

The regression results obtained are analysed to gather further insights. In particular, the coefficients of determination (R^2) are discussed in detail, which represent the proportion of the variance of the dependent variable that is explained by the independent variable using the proposed regression model. Other regression results discussed are the coefficients (b), in the cases when the regressions are significant and the model sufficiently explains the variance (i.e. R^2 are sufficiently high).

Apart from the regressions using service indicators, total consumption-based emissions and total primary energy use per country are included in the regressions. This allows for the correlations of these aggregated indicators to be compared with the correlations of specific services, as well as to make comparisons with the literature that considers such aggregated indicators.

The regressions consider two cross-sections of the data related to selected countries and subsequent n: (i) with the maximum n for each indicator (where n is the sample size of available countries) split by large n ($n \geq 90$) and small n ($n < 90$) to account for the variability of data availability, and (ii) with the common n (where n is the sample size of the subset of countries for which data is available for all indicators). Maximum n is to compare as much of the variance of the development indicator as possible, while common n is to be able to study the shape of the curve produced by each indicator over the regression results. Both of these cross-sections are studied for a single year (2014) and with the time-series data for the period of 2000-2015.

The time-series part of the study is carried out using the same regression at each year, doing only the cross-sections of maximum n for both large and small n. This will show how the regression results have changed over time with changing resource chains. The regressions for common n in the time-series were tried, but the results did not add any new insights due to the reduction of n, in which mostly developed countries were shown.

3.2.4 Limitations of the study

This extensive analysis in terms of number of indicators is limited by data availability and quality for several countries and indicators. Information on device ownership and energy use is scarce for many developing countries, which makes any estimations of service units and service indicators harder and more uncertain. A related limitation was having to reduce the data used in the study to allow for service regression comparisons using the same countries and years. This led to omitting some indicators in the analysis. The limitation of data quality could only be addressed by ensuring that the same source of information was used in each indicator, however there is no way to know whether there are inconsistencies in the data collection practices of each source (e.g. if the methods to acquire data were different or data for earlier years were less representative).

OLS regressions have a known limitation related to sampling variability, where any addition or removal of data points may alter the results. In this study, the results then depend on country averages of those where data is available, so changing them will certainly alter the results. This limitation is addressed by specifying which countries are considered in each regression and making observations about any biases towards specific regions. Generally, such bias tends to be towards developed and OECD countries, especially when comparing the same countries in each service regression (common n).

The OLS regressions used for the time-series data can show how the regression results have changed with changing data availability, however care needs to be exercised to not interpret the yearly regression trends in detail. This is because methods for panel data are better suited to analyse trends, but would have presented challenges related to sampling. This is because the data varies significantly and not all indicators are available for the time period selected, so a panel data study would reduce n to a point where results would not be interesting. Further, there is no assurance that the values track the same individuals over time. Since the point of this study is to show the effect of both data availability and parts of the resource chain considered in the regressions, the OLS method employed is sufficient.

The analysis in this chapter included parts of the resource chain, seeking to not be prescriptive regarding devices that deliver the services studied, e.g. communication could have been studied only with mobile phone access, however both mobile phones and landlines to deliver communication were included. Comparing the approach used in this chapter to existing literature, authors such as Rao et al. (2019) have similar thoughts in terms of services, but compare countries with each other in terms of ownership of predetermined devices. In the long run, prescribing devices may not lead to improved development, but rather the expansion of using devices for local conditions that lead to the satisfaction of the service. Nonetheless, the available data limits the study of alternative ways to provide services, so efforts to increase data collection are necessary.

3.3 Results

This section presents the results from the regressions with comparisons of interest, which are the following:

1. Two cross-sections of service and development indicators for each unique year which consider: i) the maximum sample size available (referred to as maximum n) split by large and small n to account for data availability, and ii) a subset of countries where data for all indicators are available (referred to as common n), which sets a precedent for when more information per indicator is available to compare all indicators for the same countries.

2. The regression results considering the time series of the same cross-sections of service and development indicators splitting again by large and small n.

The results are structured as follows: First, observations of the shape of the data are presented for a single year (2014) and a single development indicator in section 3.3.1. Then, the 2014 regression results considering both types of cross-sections are presented in section 3.3.2. Finally, in section 3.3.3 the time-series regression results are presented, using HDI as an example of development indicator, followed by a discussion on results for the other development indicators. The coefficients of determination (R^2) are the main point of discussion in the sections, as they allow pairs of indicators to be compared with each other as well as showing which indicators follow the proposed model. Other regression results are presented, e.g. the intercept (*a*) or the coefficient (*b*), and comments are made when appropriate. Additional details of the regression results can be found in appendix A.

3.3.1 Global energy services and HDI in 2014

Figure 3.2 presents an example of the data available in each service indicator and one development indicator (HDI). In the figure, all service indicators have normalised units (to enable comparisons of the relationships in the same graphs). The year used is 2014, since it is the year for which most indicator data are available. The n is also the highest available for each combination of service-development indicators.

Table 3.4 shows the service indicators and their shortened names for the graphs, as well as the values used to normalise each service indicator. The normalisation value is the equivalent to 100 for the x-axis index.

The shape of the scatter plots confirms the non-linear relationships between each pair of variables, with a positive relationship (leading to a positive coefficient b in the regressions) in all indicators. The spread between the data points varies between indicators, which will affect the coefficients of determination (R^2). For example, for Sustenance (subplot 6) there is more variance in the food supply indicators compared to food emissions, so the food supply indicators are expected to have a low R^2- if at all significant. Similarly, a low R^2 is expected for built space and mobile cellular subscriptions.

Table 3.4 Values used for normalisation for each service indicator.

Service indicator		*Normalisation (100 = x units)*	
Long name	Short name (for graphs)	Value (x)	Units
1 Passenger Transport			
Road vehicles	Road vehicles	89.9	veh/10K cap
Total passenger transport	Passenger transport	68.79	GJ/cap
Passenger-kilometres	Passenger-kilometres	28.19	10^3 pkm/cap
Motor vehicles, trailers and semi-trailers	Transport emissions	39.72	kg CO_2/10^5cap
2 Freight Transport			
Total freight transport	Freight transport	32.59	GJ/cap
Tonne-kilometres	Tonne-kilometres	32.08	10^3 tkm/cap
Motor vehicles, trailers and semi-trailers	Transport emissions	39.72	kg CO_2 /10^5cap
3 Residential thermal comfort			
Residential space cooling	Residential cooling	3.14	GJ/cap
Residential space heating	Residential heating	31.8	GJ/cap
Built space	Built space	546.29	km^2 /cap
Utilities emissions	Utilities emissions	641.79	kg CO_2/Mcap
Domestic households	Household emissions	24.39	kg CO_2/Mcap
4 Services thermal comfort			
Services space cooling	Services cooling	410.0	10 MJ/cap
Services space heating	Services heating	1712.9	10 MJ/cap
Built space	Built space	546.29	km^2 /cap
Utilities emissions	Utilities emissions	641.79	kg CO_2/Mcap
5 Communication			
Fixed telephone subscriptions	Fixed telephone	132.72	number/100 cap
Mobile cellular subscriptions	Mobile	321.8	number/100 cap
Televisions	Televisions	122.22	10 MJ/cap
Personal computers	Personal computers	71.62	10 MJ/cap
IT and other information services	IT emissions	34.77	kg CO_2 /10^5cap
Telecommunications	Telecomms emissions	30.0	kg CO_2 /10^5cap
Computer, electronic and optical products	Electronics emissions	84.79	kg CO_2 /10^5cap
Publishing, audiovisual and broadcasting activities	Publishing emissions	12.0	kg CO_2 /10^5cap
6 Sustenance			
Prevalence of obesity in the adult population (18 years and older)	Obesity	60.7	%
Fat supply quantity	Fat supply	167.64	g/cap/day
Food supply	Food supply	38.45	kcal/100cap/day
Protein supply quantity	Protein supply	141.01	g/cap/day
Residential cooking	Residential cooking	56.0	100 MJ/cap
Refrigerators	Refrigerators	50.0	10 MJ/cap
Freezers	Freezers	80.0	10 MJ/cap
Refrigerator/Freezer combinations	Refrigerator/Freezer	161.05	10 MJ/cap
Food products, beverages and tobacco	Food emissions	15.94	kg CO_2/Mcap
Domestic households	Household emissions	24.39	kg CO_2/Mcap
7 Health			
Adult mortality rate	Adult mortality	69.69	prob/100cap
Births attended by skilled health personnel	Births attended	100.0	%
Hospital beds	Hospital beds	143.0	beds/10K cap
Medical doctors	Medical doctors	84.22	doctors/10K cap
Human health and social work	Health emissions	33.33	kg CO_2 /10^5cap

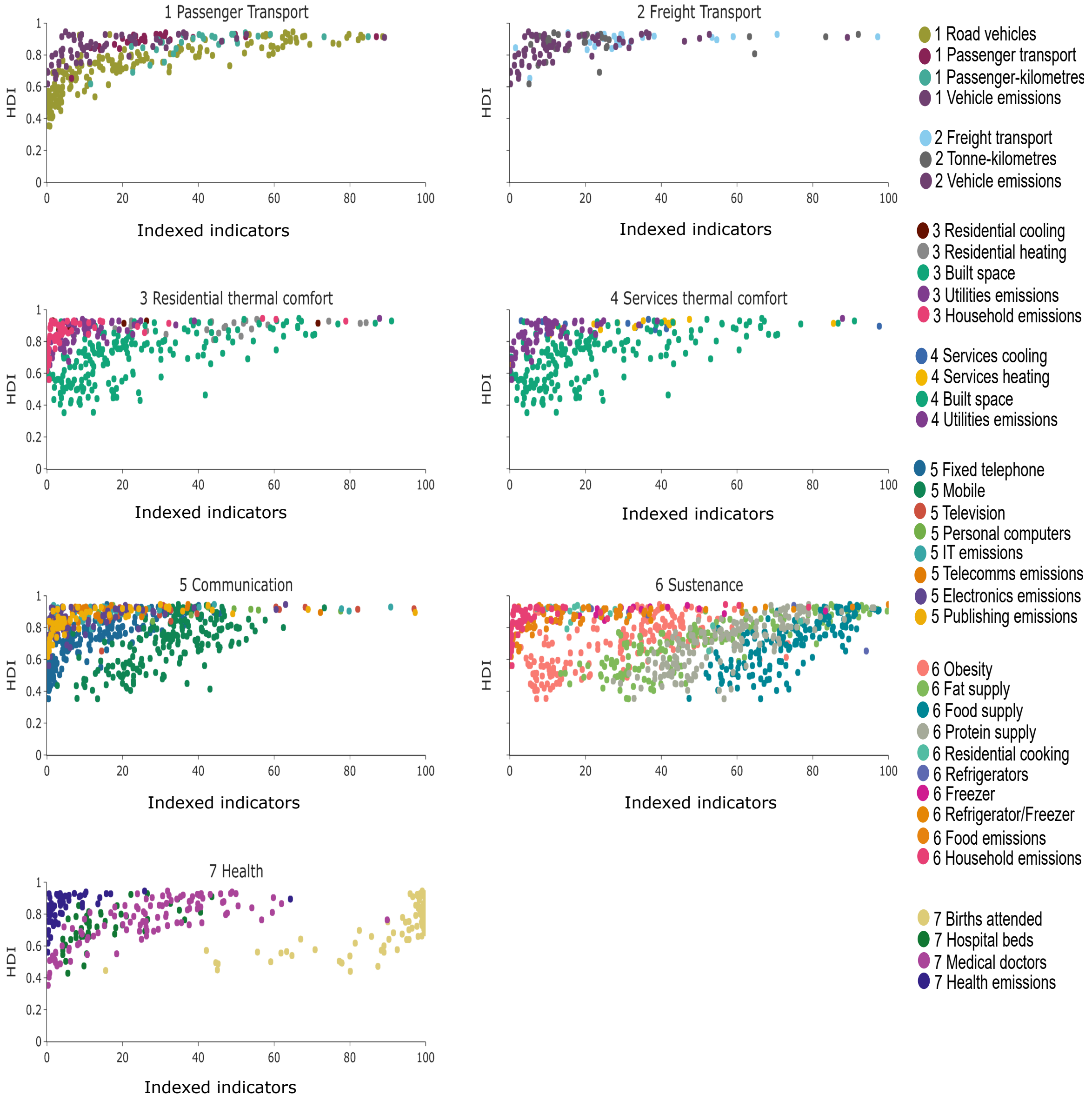


Fig. 3.2 Normalised service provision indicators and HDI for 2014. The labels to the right are presented in numbered groups according to the service order. Consult table 3.4 for details.

3.3.2 Single-year cross-sections of global energy services and development indicators

The following regression results consider only the year of 2014. In them, the two types of cross-sections are studied: (1) using the highest possible sample size for each pair of indicators (maximum *n*) splitting by large and small *n*, and (2) using a subset of countries where the same data is available for each service indicator (common *n*). All service indicators are normalised. The results also include total emissions and primary energy.

Maximum *n* cross-section split by large *n* in 2014

Regressions using the maximum *n* enable comparisons of as much of the variance as possible in each pair of indicators. Further, the split of large *n* is used to compare the indicators where most countries are represented.

Table 3.5 shows the results of the regressions of those regressions which produced significant results. The results include the sample size (n), intercept (a), coefficient (b) and coefficient of determination (R^2) for each pair of indicators. As expected, some regressions had low R^2 (e.g. prevalence of obesity), and the model did not produce results for every indicator with a large *n* (e.g. mobile phones). The latter indicates that this model is not good for explaining the relationship between some service provision indicators, which had not been observed before in the literature.

The service provision indicators where most variance of development indicators can be explained (highest fit) is road vehicle ownership with HDI and IHDI (R^2 of 0.81 and 0.79 respectively), followed by fixed telephone subscriptions with HDI and IHDI (R^2 of 0.78 and 0.76 respectively). The curves of both indicators have similar magnitude and direction, based on the coefficients obtained. Considering that HDI and IHDI are compound indicators, the high R^2 can be attributed to high correlations with the components of LExB and EYSch. Both of these service indicators are linked to devices in the resource chain.

The results of the type of service provision indicator that produced significant regression results (i.e. primary and final energy, device ownership, and emissions) are discussed further below:

- **Final energy indicators**: No final energy indicator had a sufficiently large *n* in this data split.
- **Device ownership indicators**: The highest *n*'s in this cross-section are for the indicators of fixed telephone subscription, prevalence of obesity and road vehicle ownership. The regressions with these indicators all produce significant results, albeit those with prevalence of obesity have the lowest R^2. This means that, generally, device ownership indicators have the highest R^2, which implies most of the variance of each development indicator may be explained best with some ownership indicators, compared to other resource chain indicators. The implications of this finding should be carefully examined, so they will be further addressed in the discussion.

- **Total primary energy indicator**: The regressions using the aggregate value of total primary energy was able to be studied with the model proposed with significant results. Among the development indicators correlated with primary energy, the highest fits are observed with IHDI, HDI and GNI (R^2 values of 0.71, 0.68 and 0.69 respectively). This suggests that increases in income impacts the high R^2 using compound indicators.

- **Emission indicators**: No emissions related to individual services or total emissions were significant within this data split.

Table 3.5 Results of large *n* regressions in 2014.

	HDI				IHDI				AvYSch				EYSch				GNI				LExB			
Service indicator	n	R^2	a	b	n	R^2	a	b	n	R^2	a	b	n	R^2	a	b	n	R^2	a	b	n	R^2	a	b
1 Passenger Transport																								
Road vehicles	181	0.81[1]	0.50	0.09	148	0.79[1]	0.33	0.11	181	0.68[1]	4.59	1.66	184	0.59[1]	9.95	1.40	150	0.47[1]	-712.23	8308.46	183	0.65[1]	62.05	4.14
5 Communication																								
Fixed telephone	183	0.78[1]	0.56	0.08	147	0.76[1]	0.41	0.09	184	0.64[1]	5.80	1.52	185	0.59[1]	10.82	1.34	151	0.33[1]	7167.73	6947.66	191	0.73[1]	64.56	4.12
6 Sustenance																								
Obesity	183	0.44[1]	0.34	0.14	149	0.43[1]	0.12	0.17	184	0.44[1]	0.89	2.79	185	0.31[1]	7.28	2.17	150	0.22[1]	-13360.80	12022.36	181	0.34[1]	54.38	6.38
7 Health																								
Births attended	112	0.42[1]	-0.78	0.34	91	0.37[1]	-1.11	0.38	112	0.39[1]	-22.04	6.94	112	0.28[1]	-8.67	5.02	94	0.13[1]	-103932.77	27886.99	109	0.29[1]	9.05	14.31
9 Primary energy																								
Primary energy	130	0.68[1]	0.60	0.11	111	0.71[1]	0.42	0.16	130	0.52[1]	6.50	2.00	131	0.53[1]	11.13	2.00	118	0.69[1]	-1189.78	16936.66	133	0.43[1]	67.61	4.45

[1] Significant at $P \leq 0.01$.

Maximum *n* cross-section split by small *n* in 2014

Regressions using the maximum *n* enable comparisons of as much of the variance as possible in each pair of indicators. In this case, those indicators with small *n* are used.The countries missing in some indicators are mainly developing ones, thus this split of data allows for developed- mainly OECD- countries to be compared.

Table 3.6 shows the results of the regressions of those regressions which produced significant results. The results include the sample size (n), coefficient of determination (R^2), intercept (a) and the coefficient (b) for each pair of indicators. As expected, some regressions had low R^2 (e.g. residential space cooling), and the model did not produce results for every indicator (e.g. built space). As with the large *n* split, this indicates that the model and its constrained *n* are not good for explaining the relationship between some service provision indicators.

The results of the type of service provision indicator that produced significant regression results are discussed further below:

- **Final energy indicators**: Most final energy indicators have small *n*'s (from minimum 5 for refrigerators to maximum 30 for residential space heating). It may be argued that the sample size affects the validity of the model, since at small *n*'s only part of the curve may be contained due to the indicators covering mostly OECD countries, where saturation values have been attained. This is likely true in some instances where the model did not produce results. It is only an exception for final energy for passenger and freight transport, because both have the same *n* (n = 27), but only freight transport is both significant and able to produce results with the proposed model. Such regression of final energy for freight transport is only significant with a low fit with LExB (R^2=0.31, n = 27). Apart from freight transport, services space cooling was also significant with low fits for HDI (R^2=0.35, n = 15) and LExB (R^2=0.47, n = 15), while residential space cooling produced results, but none were significant.

- **Device ownership indicators**: No regressions were significant within this data split because many device ownership indicators have a large *n*.
- **Total primary energy indicator**: No regressions were significant within this data split because primary energy has a large *n*.
- **Emission indicators**: The regressions using the aggregate values of total embodied emissions were able to be studied with the model proposed with significant results. The correlations show moderate fits, obtaining the highest correlations with HDI (R^2=0.69), IHDI (R^2=0.65) and GNI (R^2=0.64). No emissions related to individual services were significant within this split of data.

Table 3.6 Results of small *n* regressions in 2014.

	HDI				IHDI				AvYSch				EYSch				GNI				LExB			
Service indicator	n	R^2	a	b	n	R^2	a	b	n	R^2	a	b	n	R^2	a	b	n	R^2	a	b	n	R^2	a	b
2 Freight Transport																								
Freight transport	27	0.29[1]	0.76	0.04	26	0.15[3]	0.67	0.04					27	0.21[2]	13.39	1.04	27	0.22[2]	14580.48	6959.07	27	0.31[1]	75.67	1.59
4 Services thermal comfort																								
Services cooling	15	0.35[2]	0.79	0.03																	15	0.47[1]	78.24	1.15
8 Emissions																								
Total emissions	63	0.69[1]	0.53	0.10	56	0.65[1]	0.31	0.14	63	0.55[1]	3.93	2.16	63	0.43[1]	10.41	1.70	61	0.64[1]	-27148.03	18338.85	63	0.32[1]	66.71	3.58

[1] Significant at $P \leq 0.01$.

[2] Significant at $P \leq 0.02$.

[3] Significant at $P \leq 0.05$.

Common *n* cross-section in 2014

The regression results using the common *n* cross-section show how each pair of indicators fit the proposed model in the same countries for each service category. The aim of this cross-section is to set a precedent of how all service indicators may be compared with the same country and year. This cross-section facilitates making comparisons of the different indicators for each service, but has a cost of producing a small *n*. In this cross-section, all service indicators are normalised and the indicators of total emissions and total primary energy within each service are also included, to compare the same countries.

Table 3.8 shows the results of the regressions for each pair of indicators for this cross-section, while table 3.7 shows the specific countries considered in each indicator. As expected, there was an increase in significant regressions and a loss of data points, leading the maximum n to be 22 (in Transport indicators) and the lowest to be 11 (for Residential thermal comfort indicators). Health indicators were not presented in this data split, due to their low n related to the lack of data for 2014 in all Health indicators. In Health regressions for other years there is a higher n of up to 28, because more indicators contain data.

There is a marked influence of the countries and number of samples used on how well the model works. Sustenance regressions produced low R^2 overall, even if their n was the same as Communication ($n = 14$). This is due to the countries considered, where Communication includes Morocco, thus being able to represent more variance among the indicators and producing a higher R^2. This is reflected in the values of b, with lower b when Morocco was considered. Graphically, this means the slope is steeper with the inclusion of developing countries. Morocco was included in the regressions for Communication and Services Thermal Comfort.

The indicators that fitted the model best and thus had the highest R^2 are those for Services (the sector) Thermal Comfort, particularly HDI versus services space heating ($R^2 = 0.91$, n = 13), as well as IHDI and utilities' emissions ($R^2 = 0.86$, n = 12). Part of the reason for these being the highest fits is the inclusion of developing countries, where the data for Services (the sector) Thermal Comfort includes Morocco as seen in Table 3.7.

The curves obtained with this cross-section tended to have a positive b coefficient. In many cases, the prevalence of developed countries in the cross-section, led to curves with smaller b's and higher a's, leading to steeper curves that were situated higher than the regressions with at least one developing country, e.g. the regressions of total emissions for Thermal Comfort (with a going from 0.05 to 0.10 and b from 0.72 to 0.54 for residential- only developed- and the services sector- with Morocco- respectively). It can then be generalised, that the inclusion developing countries in regressions leads to steeper curves with a more realistic a.

The only case where the b coefficient is negative is in the regression of final energy for residential cooking. Therefore, the curve of residential cooking would tend to have a lower value of final energy with increasing values of development. This suggests a shift in cooking behaviour as with higher levels of development, which should be studied further and with a larger n.

Comparing the different development indicators used per service, and ignoring the indicators of total primary energy and total emissions- which will be discussed separately-, the following observations arise:

- **Compound development indicators**: The best-performing models with aggregated development indices (HDI, IHDI) are those linked to final energy for services (the sector) space heating, followed by utilities' emissions.
- **Life expectancy indicator**: The highest fits with life expectancy (LExB) amongst all the service indicators is that with fixed telephone subscriptions ($R^2 = 0.74$, n = 14).
- **Schooling indicators**: The highest fits with schooling indices (EYSch, AvYSch) are those linked to final energy for services (the sector) space heating ($R^2 = 0.78$ and $R^2 = 0.61$ for AvYSch and EYSch respectively, n = 13). In general, EYSch tends to have lower R^2 values than AvYSch in the regressions.
- **Income indicator**: The highest fits with GNI are those related to final energy for Services (the sector) Space Heating ($R^2 = 0.78$, n = 13).

The addition of total primary energy and total emissions to the regressions using the common *n* split produced two key findings: First, that the proposed model showed the highest fits with total primary energy and total emissions with AvYSch and GNI (R^2 up to 0.86), leading to some similarly high values of HDI - yet surprisingly few of IHDI (which also has a higher *b* than HDI, showing the inclusion of inequality leads to a steeper curve). The highest values of R^2 were also obtained with those service categories where Morocco was included. Second, that the model performed worst with total primary energy and total emissions with the indicators of EYSch and LExB.

The results of the type of service provision indicator that produced significant regression results (i.e. primary and final energy, device ownership, and emissions) are discussed further below:

- **Final energy indicators**: Correlations with final energy indicators are better at explaining the variance of each development indicator in the services of Passenger Transport, Services Thermal Comfort and Sustenance. This is shown by the R^2, where final energy indicators are higher than those of total primary energy (e.g. passenger transport final energy is 0.52, whereas primary energy is 0.47).
- **Device ownership indicators**: Correlations with device ownership indicators only showed higher R^2 than the other service provision indicators in the case of fixed telephone subscriptions with LExB, HDI and EYSch (R^2 = 0.74, 0.69 and 0.40 respectively,

n = 22), and road vehicle ownership with LExB (R^2 = 0.29, n = 22). Furthermore, in both regressions with LExB, the curve resulted steeper than the rest of the indicators based on higher values of *b*. The latter shows that device access and life expectancy have similar dynamics.

- **Emission indicators**: Correlations with service-related emission indicators were mostly better than total emissions at explaining the variance of each development indicator. The only exception was for utilities' emissions with HDI in the sector of Services Thermal Comfort ($R^2 = 0.79$) compared to total emissions ($R^2 = 0.70$, with n = 13 for both). In the other cases, service-related emissions are lower than those for total emissions (e.g. the R^2 of transport emissions is 0.22 and total emissions is 0.46 with HDI).

Table 3.7 Countries in common *n* regressions for 2014

Service	n	Country names
Transport	22	Australia, Austria, Belgium, Canada, Czech Republic, France, Germany, Greece, Hungary, Ireland, Italy, Japan, South Korea, Luxembourg, Netherlands, New Zealand, Poland, Portugal, Slovakia, Spain, Sweden, United States
Residential thermal comfort	11	Australia, Canada, France, Germany, Greece, Italy, Japan, South Korea, Portugal, Spain, United States
Services thermal comfort	13	Canada, France, Germany, Italy, Japan, South Korea, Morocco, Netherlands, New Zealand[a], Portugal, Spain, Sweden, United States
Communication	14	Australia, Austria, Canada, Czech Republic, France, Germany, Italy, South Korea, Morocco, Netherlands, New Zealand, Portugal, Slovakia, United States
Sustenance	14	Australia, Austria, Canada, Czech Republic, Denmark, Finland, France, Germany, Italy, Netherlands, Portugal, Switzerland, United Kingdom, United States

[a] New Zealand was missing in the IHDI indicator.

Table 3.8 Results of common *n* regressions in 2014. Only significant results shown.

	HDI				IHDI				AvYSch				EYSch				GNI				LExB			
Service indicator	n	R^2	a	b	n	R^2	a	b	n	R^2	a	b	n	R^2	a	b	n	R^2	a	b	n	R^2	a	b
1 Passenger Transport																								
Road vehicles	22	0.21^{1}	0.63	0.06													22	0.28^{2}	-62840.67	24239.48	22	0.29^{1}	59.58	5.18
Passenger transport	22	0.52^{1}	0.74	0.05					22	0.23^{1}	7.85	1.23					22	0.50^{1}	-12461.19	15236.37				
Passenger-kilometres	22	0.40^{1}	0.67	0.06													22	0.21^{2}	-16171.01	14345.96				
Vehicle emissions	22	0.22^{3}	0.84	0.02	21	0.51^{1}	0.69	0.04													22	0.23^{3}	77.11	1.31
Primary energy	22	0.47^{1}	0.78	0.05					22	0.44^{1}	7.49	1.97					22	0.57^{1}	-4374.93	18762.02				
Total emissions	22	0.46^{1}	0.72	0.05					22	0.40^{1}	5.50	1.82					22	0.51^{1}	-22985.46	17201.36				
2 Freight Transport																								
Freight transport	22	0.24^{3}	0.83	0.02													22	0.19^{3}	18655.84	5567.76	22	0.26^{2}	76.45	1.36
Tonne-kilometres									22	0.23^{1}		0.77												
Vehicle emissions	22	0.22^{3}	0.84	0.02	21	0.51^{1}	0.69	0.04													22	0.23^{3}	77.11	1.31
Primary energy	22	0.47^{1}	0.78	0.05					22	0.44^{1}	7.49	1.97					22	0.57^{1}	-4374.93	18762.02				
Total emissions	22	0.46^{1}	0.72	0.05					22	0.40^{1}	5.50	1.82					22	0.51^{1}	-22958.46	17201.36				
3 Residential thermal comfort																								
Utilities emissions [a]	11	0.47^{3}	0.77	0.05	11	0.54^{1}	0.59	0.07	11	0.44^{3}	4.48	2.65												
Household emissions																								
Primary energy	11	0.62^{1}	0.79	0.05					11	0.66^{1}	5.42	2.82					11	0.65^{1}	5049.83	14436.37				
Total emissions	11	0.71^{1}	0.72	0.05					11	0.71^{1}	1.32	2.91					11	0.59^{1}	-11166.52	13561.24				
4 Services thermal comfort																								
Services cooling	13	0.36^{3}	0.79	0.03																	13	0.45^{2}	78.24	1.13
Services heating	13	0.91^{1}	0.75	0.05	12	0.85^{1}	0.59	0.06	13	0.78^{1}	7.23	1.38	13	0.61^{1}	14.07	0.81	13	0.78^{1}	16853.54	6602.44	13	0.48^{1}	78.45	1.00
Built space					12	0.35^{3}	0.37	0.11									13	0.36^{1}	-9154.14	11978.20				
Utilities emissions [a]	13	0.79^{1}	0.71	0.07	12	0.86^{1}	0.52	0.10	13	0.68^{1}	6.23	2.04	13	0.31^{3}	14.17	0.92	13	0.68^{1}	11927.30	9851.59	13	0.63^{1}	76.91	1.81
Primary energy	13	0.82^{1}	0.67	0.10	12	0.65^{1}	0.51	0.13	13	0.86^{1}	4.31	3.27	13	0.46^{2}	13.05	1.60	13	0.79^{1}	4167.05	15041.85	13	0.27	77.77	1.69
Total emissions	13	0.70^{1}	0.54	0.10	12	0.48^{2}	0.37	0.12	13	0.83^{1}	-0.90	3.61	13	0.31^{3}	11.47	1.48	13	0.73^{1}	-18605.71	16278.30				
5 Communication																								
Fixed telephone	14	0.69^{1}	0.55	0.10	13	0.50^{1}	0.38	0.12	14	0.39^{2}	3.55	2.46	14	0.40^{2}	9.92	2.03	14	0.58^{1}	-13781.04	15110.65	14	0.74^{1}	69.58	3.38
IT emissions	14	0.61^{1}	0.77	0.05	13	0.66^{1}	0.62	0.07	14	0.61^{1}	8.00	1.53	14	0.30^{3}	14.50	0.88	14	0.46^{1}	19765.63	6727.22				
Telecomms emissions	14	0.32^{3}	0.83	0.03	13	0.43^{2}	0.70	0.05	14	0.34^{3}	10.09	0.96					14	0.30^{3}	28439.73	4584.61				
Electronics emissions	14	0.67^{1}	0.75	0.05	13	0.58^{1}	0.61	0.06	14	0.52^{1}	7.92	1.38	14	0.38^{2}	14.02	0.96	14	0.52^{1}	17187.55	6901.39	14	0.44^{1}	77.23	1.27
Publishing emissions	14	0.51^{1}	0.80	0.03	13	0.52^{1}	0.67	0.05	14	0.44^{1}	9.13	1.01					14	0.41^{2}	26341.91	4878.99	14	0.48^{1}	78.06	1.04
Primary energy	14	0.85^{1}	0.66	0.10	13	0.65^{1}	0.51	0.13	14	0.84^{1}	4.59	3.22	14	0.47^{1}	12.25	1.99	14	0.70^{1}	3192.23	14921.37	14	0.31^{3}	76.36	1.96
Total emissions	14	0.79^{1}	0.52	0.10	13	0.55^{1}	0.36	0.12	14	0.76^{1}	0.35	3.27	14	0.54^{1}	8.82	2.25	14	0.73^{1}	-19965.20	16145.16				
6 Sustenance																								
Food supply													14	0.34^{3}	92.13	-16.68								
Residential cooking	14	0.55^{1}	1.01	-0.04	14	0.43^{2}	0.96	-0.05																
Freezer	14	0.32^{3}	0.80	0.03													14	0.35^{3}	3761.78	10688.85				
Primary energy									14	0.32^{3}	7.98	1.89												
Total emissions	14	0.45^{1}	0.74	0.05					14	0.51^{1}	3.45	2.46					14	0.30^{3}	-2279.45	12165.81				

[a] Utilities emissions refers to emissions classified as: Electricity, gas, water supply, sewerage, waste and remediation services.

[1] Significant at $P \leq 0.05$.

[2] Significant at $P \leq 0.02$.

[3] Significant at $P \leq 0.05$.

3.3.3 Time-series cross-sections of global energy services and development indicators

In this section, time-series regression results are described using the cross-section of maximum *n* split by large and small *n*. All service indicators are normalised.

Time-series data split by large *n*

Figure 3.3 shows the curves obtained for the regressions using indexed indicators for the split of large *n* between 2000 and 2016, where the lighter shade represents the lower value of the year indicated below each subplot.

Table 3.9 shows further details of such regression results, including *a*, *b*, R^2 and *n* for each pair of indicators. The only development indicator for which data is not available prior to 2010 is IHDI, since that was the year when the indicator was first used. The only service indicator with no time-series data is passenger vehicle ownership, which was only reported for 2014 in the data source used.

The time-series results show that the same indicators as in the 2014 maximum *n* are significant and that in each service only one regression for a single service provision indicator is significant, e.g. for the service of Communication only the regressions of fixed telephone subscriptions are significant.

The highest *n*'s in this cross-section are for the indicators of fixed telephone subscription, prevalence of obesity and road vehicle ownership, with the first two having almost the same values of *n* over time. The high *n* of the three indicators is in line with the results for 2014. The regressions with these indicators all produce significant results, albeit those with prevalence of obesity have the lowest R^2 (from 0.2 up to 0.4, depending on the development indicator). This means that, overall, device ownership indicators have the highest R^2, which suggests that most of the variance of each development indicator may be best explained with some ownership indicators, compared to other resource chain indicators. This statement needs to be considered carefully, so it will be further addressed in the discussion.

The regression curves show that for constant service-related levels, the development indicators are increasing over time (the curve shifts up), which can be interpreted as decoupling of development from the service indicators shown.

Other regression results in this section will be discussed depending on the type of development indicators (compound and non-compound).

Compound development indicators:

- The highest R^2 for both compound development indicators are in the regressions with fixed telephone subscriptions and road vehicle ownership. In the case of fixed telephone subscriptions, the value of R^2 decreases over time, implying fixed telephone subscriptions are able to explain the variance of development indicators less over time (e.g. the R^2 in the regression against HDI goes from 0.85 to 0.76 in 2005 and 2015 respectively). This decrease is not related to *n*, since *n* has remained constant, which implies the decrease of fixed telephone subscriptions in recent years that has given way to mobile ones is affecting the regression. Similarly, primary energy shows a decreasing value of R^2 over time, implying primary energy is able to account for changes in compound development indicators less over time (with R^2 going from 0.74 to 0.68 between 2000 and 2014).

Non-compound development indicators:

- Graphically, the curves with primary energy and non-compound indicators are both steeper and found above all other indicators. The regressions between primary energy and GNI are the ones with the highest R^2 values (i.e. more GNI variance may be explained with primary energy). The points of GNI and primary energy also point to the possibility of fitting a linear function to compare if a better fit can be obtained.
- The regressions of prevalence of obesity and AvYSch have the highest R^2 (above 0.4), among its other regressions with non-compound development indicators. That means prevalence of obesity can best explain the variance of AvYSch, even if the R^2 value means that the fit is moderate.

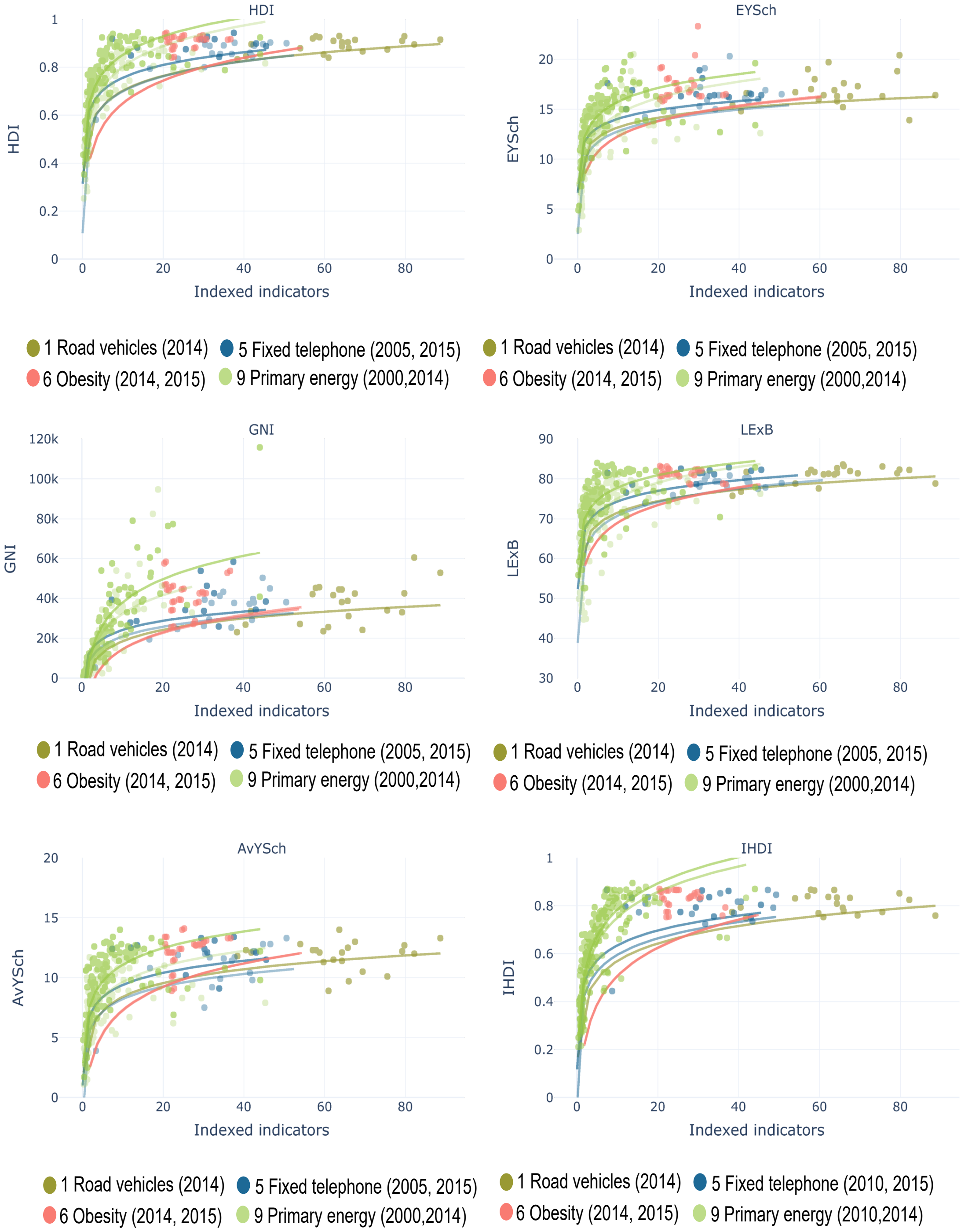


Fig. 3.3 Time-series regression results of service and development indicators with large n for the maximum n cross-section. The number before the service indicator refers to the service categories, preserving the order shown in Figure 3.2. The lighter shade in each service indicator represents the lower value of the year indicated below each subplot. Detailed results are shown in Table 3.9. All curves have $P \leq 0.05$.

Table 3.9 Time-series results of large *n* regressions. Only significant results are shown.

	Year	HDI				IHDI				AvYSch				EYSch				GNI				LExB			
Service indicator		n	R^2	a	b	n	R^2	a	b	n	R^2	a	b	n	R^2	a	b	n	R^2	a	b	n	R^2	a	b
1 Passenger Transport																									
Road vehicles	2014	181	0.81^{1}	0.50	0.09	148	0.79^{1}	0.33	0.11	181	0.68^{1}	4.59	1.66	184	0.59^{1}	9.95	1.40	150	0.47^{1}	-712.23	8308.46	183	0.65^{1}	62.05	4.14
5 Communication																									
Fixed telephone	2005	182	0.85^{1}	0.49	0.09	137^{a}	$0.78^{1\ a}$	0.37^{a}	0.10^{a}	182	0.65^{1}	4.75	1.51	184	0.70^{1}	9.17	1.57	137	0.37^{1}	4356.74	7145.17	193	0.74^{1}	59.54	4.90
Fixed telephone	2015	183	0.76^{1}	0.58	0.08	147	0.74^{1}	0.43	0.09	183	0.64^{1}	6.05	1.45	185	0.57^{1}	11.09	1.28	147	0.34^{1}	8697.67	6680.36	190	0.70^{1}	65.57	3.83
6 Sustenance																									
Obesity	2014	183	0.44^{1}	0.34	0.14	149	0.43^{1}	0.12	0.17	184	0.44^{1}	0.89	2.79	185	0.31^{1}	7.28	2.17	150	0.22^{1}	-13360.80	12022.36	181	0.34^{1}	54.38	6.38
Obesity	2015	183	0.43^{1}	0.33	0.14	149	0.42^{1}	0.11	0.17	184	0.43^{1}	0.76	2.83	185	0.31^{1}	7.16	2.22	147	0.22^{1}	-14421.91	12504.89	181	0.34^{1}	54.55	6.31
9 Primary energy																									
Primary energy	2000	130	0.74^{1}	0.52	0.12	112^{a}	$0.74^{1\ a}$	0.40^{a}	0.15^{a}	130	0.50^{1}	5.34	1.87	135	0.60^{1}	9.06	2.36	105	0.63^{1}	757.81	13610.17	137	0.44^{1}	62.09	5.67
Primary energy	2014	130	0.68^{1}	0.60	0.11	111	0.71^{1}	0.42	0.16	130	0.52^{1}	6.50	2.00	131	0.53^{1}	11.13	2.00	118	0.69^{1}	-1189.78	16936.66	133	0.43^{1}	67.61	4.45

[1] Significant at $P \leq 0.01$.

[a] The regression with IHDI does not have 2005 results since the indicator began in 2010, so results for 2010 are presented instead.

Time-series data split by small *n*

Figure 3.4 shows the curves obtained for the regressions using indexed indicators for the split of large *n* between 2000 and 2016, where the lighter shade represents the lower value of the year indicated below each subplot.

Table 3.10 shows further details of such regression results, including *a*, *b*, R^2 and *n* for each pair of indicators.

Similarly to large *n*, the regression curves show that for constant freight transport, service cooling and total emission levels, the development indicators are increasing over time (the curve shifts up), which can be interpreted as decoupling of development from the service indicators shown. Total emissions are generally decoupling with compound development indicators, yet the regressions with their components show that total emissions are decoupling from schooling indicators (e.g.for AvYSch, the R^2 goes from 0.60 to 0.55 between 2005 and 2015), but are coupling more with GNI (R^2 goes from 0.55 to 0.65 between 2005 and 2015).

Other regression results in this section will be discussed depending on the type of development indicators (compound and non-compound).

Compound development indicators:

- The highest R^2 for both compound development indicators is with total emissions (R^2 of 0.70 and 0.68 for HDI and IHDI respectively in 2015).
- Two final energy indicators were significant within this data split, but only against HDI: freight transport, which has a low R^2, which implies the variance of HDI is barely explained by the model and the countries included; and services cooling. Services space cooling has a higher R^2 (0.35) than final energy for freight transport (0.15-0.28). Thus, the variance of HDI can be better explained with services cooling, even when

cooling has a lower *n* than freight transport, since freight transport ends up closer to a straight line than cooling.

Non-compound development indicators:

- The regression of total emissions and GNI produced the highest R^2, among the significant regressions in this split. The value of R^2 shows a slight increase over the time period shown (from 0.55 to 0.65 between 2005 and 2015), with the curve shifting upward in 2015.
- The regression of final energy for freight transport and LExB is significant for all the years available and has a similar value of R^2 to the regression with HDI.
- The regressions of final energy for service (the sector) cooling are only significant for LExB with a moderate fit ($R^2 = 0.47$ in 2014).

Fig. 3.4 Time-series regression results of service and development indicators with small n for the maximum n cross-section. The number before the service indicator refers to the service categories, preserving the order shown in Figure 3.2. The lighter shade in each service indicator represents the lower value of the year indicated below each subplot. Detailed results are shown in Table 3.10. All curves have $P \leq 0.05$.

Table 3.10 Time-series results of small n regressions. Only significant results are shown.

	Years	HDI				IHDI				AvYSch				EYSch				GNI				LExB			
Service indicator		n	R^2	a	b	n	R^2	a	b	n	R^2	a	b	n	R^2	a	b	n	R^2	a	b	n	R^2	a	b
2 Freight Transport																									
Freight transport	2005	26	0.28[1]	0.78	0.02													26	0.18[3]	7952.24	8760.47	26	0.29[1]	73.37	1.56
Freight transport	2015	27	0.15[3]	0.81	0.02									27	0.15[3]	14.09	0.91					27	0.17[3]	77.40	1.05
4 Services thermal comfort																									
Services cooling	2014	15	0.35[2]	0.79	0.03																	15	0.47[1]	78.24	1.15
8 Emissions																									
Total emissions	2005	63	0.77[1]	0.49	0.10	55[a]	0.73[1] [a]	0.28[a]	0.04[a]	63	0.60[1]	3.50	2.01	63	0.52[1]	9.13	1.76	60	0.55[1]	-23299.58	16189.27	63	0.33[1]	64.63	3.43
Total emissions	2015	63	0.70[1]	0.53	0.10	56	0.68[1]	0.30	0.14	63	0.55[1]	3.90	2.20	63	0.40[1]	10.16	1.82	61	0.65[1]	-29682.69	19366.00	63	0.34[1]	66.62	3.63

[1] Significant at $P \leq 0.01$.

[2] Significant at $P \leq 0.02$.

[3] Significant at $P \leq 0.05$.

[a] The regression with IHDI does not have 2005 results since the indicator began in 2010, so results for 2010 are presented instead.

3.4 Discussion

In this chapter, regressions have been undertaken to systematically study the nature of the correlations between several service provision indicators and their respective country development levels. The aim is to understand the degree to which service provision indicators are correlated with well-being delivered. The development levels have been studied using compound (HDI, IHDI) and non-compound development outcomes (life expectancy, income, education). Different countries have been considered in the regressions by using the maximum and common sample size (n) cross-sections for each pair of indicators, the former to compare as much of the variance in both indicators as possible, and the latter to compare each type of service indicator in the same countries. The cross-section of maximum n has been used to study regressions for a single year and for time-series, splitting the results by large and small n. The cross-section of common n has been used only for the results of a single year to set a precedent where all indicators are compared using the same countries. The regression results included the values of the coefficient of determination (R^2), which express the degree of correlation, and the intercept a and coefficient b from the curve obtained.

Generally, the regression curves showed that for constant service-related levels, the development indicators are increasing over time (with the curves shifting up), which can be interpreted as decoupling of development from the service indicators shown. This is in line with the observations of Steinberger and Roberts (2010) (who compare primary energy and carbon emissions with HDI and its components).

The rest of this section will address the implications of the regressions and is structured as follows: the main findings from a development perspective have been separated by compound and non-compound indicators which are shown in sections 3.4.1 and 3.4.2 respectively. Key takeaways from the study are elucidated in section 3.4.3. Finally, wider implications of the study are discussed in section 3.4.4.

3.4.1 Discussion around compound development indicators

The results of the regression analyses from the perspective of compound development indicators are discussed below combining insights for regressions and the different cross-sections used.

The results with the highest n and highest R^2 from this study are the following: The regression producing the highest R^2 with HDI has been fixed telephone subscriptions, which decreased over time (from $R^2 = 0.85$ in 2005 to 0.76 in 2015). A similarly high R^2 was obtained with road vehicle ownership with HDI ($R^2 = 0.81$) in 2014. Since this indicator was only available for that year, there is no way to know how changes in vehicle ownership have changed when compared to HDI.

Comparing the results with the highest n and highest R^2 from this study and those of Steinberger and Roberts (2010) and Arto et al. (2016), there are several observations to make. First, that the functional forms of the curve in this chapter are the same as Arto et al. (2016), using a semi-logarithmic form, while the functional form is different compared to Steinberger and Roberts (2010), who use a hyperbolic form. Second, that this study has the highest n and the highest inclusion of developing countries, among the three studies, which addresses one of the self-declared shortcoming of the database used by Arto et al. (2016). Since the years included in the studies allow for comparisons to be made, it is observed that, generally, the curves produce similar values of R^2 (e.g. the regression between primary energy and HDI resulted in $R^2 = 0.74$ in 2000, $n = 130$ for this study and $R^2 = 0.75$ in 2000, $n = 93$ for Steinberger and Roberts). Both studies also agree on the fact that decoupling seems to be occurring between the indicators. When comparing with the results of this chapter against those from Arto et al. (2016), it can be observed that both studies obtain an upward-shifting curve over time using primary energy (this study) and total primary energy footprint (Arto et al., 2016). Finally, and most importantly, this study shows that the correlations of some devices and HDI are similar to those observed with energy and emissions. Thus, the study presented in this chapter goes further in the indicators included than Steinberger and Roberts (2010) and Arto et al. (2016), finding that it is possible to study some indicators related to parts of the chain using the proposed semi-logarithmic curve. Particularly, the indicators of fixed telephone subscriptions and road vehicle ownership are well-represented by the curve, obtaining high R^2 with compound development indicators. Further, the R^2 in this study of fixed telephone subscriptions are decreasing over time, like primary energy from Steinberger and Roberts. This study also finds which indicators could be studied using a different functional form (e.g. passenger kilometres, vehicle emissions, built space, food supply, among others), concluding that the dynamics between different parts of the resource chain are not the same, needing to study each part further to find all the fitting functional forms.

In the case of the common *n* cross-section, the results showed that final energy indicators (for the services of Passenger Transport, Services Thermal Comfort and Sustenance) and primary energy (for the services of Freight Transport and Communication) were those indicators which led to a higher R^2 with the model proposed compared to the other parts of the chain with significant regressions. This implies that the dynamics of the indicators and services considered should be studied individually before assuming that an improvement in any part of the resource chain will lead to increased development at the same rate as other parts. Further, the result shows that three services can be studied from a final energy perspective. Note that this is beyond just household electricity, since Passenger Transport is included.

The correlations using the individual parts of the compound indicators show to be important for the regressions of compound indicators. Thus, since final energy for freight transport was significant with EYSch, it was also significant for HDI. Furthermore, the higher the number of components with significant results and high R^2, the higher the R^2 of the compound indicator, e.g. fixed telephone subscriptions in 2014 with LExB and schooling indicators are significant and produce high R^2, which makes HDI have a high R^2 too. This implies that non-compound development indicators are useful to study the relationship between service provision and development. Non-compound indicators are then addressed in the next section.

3.4.2 Discussion around non-compound development indicators

The results of the regression analyses from the perspective of non-compound development indicators are discussed below combining insights for regressions using both maximum and common *n*.

In this study, the non-compound development indicators used included GNI, LExB, EYSch and AvYSch, since they are the main HDI components. In the literature, only Steinberger and Roberts (2010) carried out a similar comparison, while later studies have focused mostly on LExB (Lamb and Rao, 2015; Steinberger et al., 2020). Further, the use of indicators that are closer to end-uses has been encouraged in the literature and attempted in this study.

Generally, the results of the correlations using non-compound indicators produce higher differences depending on the development indicator, whereas compound ones are correlated as long as one of the components is. The results with the highest n and highest R^2 from this study are similar to those using compound development indicators. The regression producing the highest R^2 has been fixed telephone subscriptions with both LExB and EYSch. In both cases, R^2 decreased over time (from $R^2 = 0.74$ in 2005 to 0.70 in 2015 for LExB and $R^2 = 0.70$ in 2005 to 0.57 in 2015 for EYSch). A similarly high R^2 was obtained with road vehicle ownership with AvYSch and LExB (R^2 = 0.68 and 0.65 respectively) in 2014.

The results also pointed to the possibility of using other functional forms to study the relationships between the pairs of variables. A good example is the scatterplot of GNI and primary energy, where a linear function might be used to compare if a better fit can be obtained.

The results with non-compound indicators can also be compared with Steinberger and Roberts (2010), leading to the following observations: In contrast to compound indicators, the values of R^2 resulted lower in this study than Steinberger and Roberts, e.g. the R^2 of LExB with total primary energy for this study was 0.44 in 2000 (n = 137), whereas Steinberger and Roberts reported it as 0.66 in 2000 (n = 110). The difference of n suggests that the inclusion of more developing countries changed the shape of the curves, leading to lower fits with the model in this study, yet n did not seem to affect compound indicators in the previous section. Thus, the difference may be attributed to the functional form of the curve, with a hyperbolic seeming a better option for these two indicators.

The results in this chapter show that increases in primary energy and embodied emissions can account for two thirds of the variance of GNI, and about half of the variance of schooling indicators. In contrast, life expectancy has a higher disparity, with emissions being able to account for a third of the variance of LExB, and primary energy for slightly less than half. In particular, total embodied emissions had the best fits with GNI (R^2 = 0.64, n = 61 in 2014) and AVYSch (R^2= 0.55, n = 63 in 2014), whereas total primary energy had the best fits with GNI (R^2 = 0.69, n = 118 in 2014) and schooling indicators (both around R^2 of 0.52, n = 130 in 2014). The regressions with total emissions also served to show that non-compound indicators need to be considered in studies, since they might have dynamics that are not visible in the study of compound indicators. This is because total emissions showed to be generally decoupling with compound development indicators, yet the regressions with their components showed that total emissions are decoupling from schooling indicators, but are coupling with GNI between 2005 and 2015.

In this chapter and for the cross-section of maximum n, specific final energy indicators have a higher or similar R^2 to non-compound development indicators than primary energy. They are freezers with GNI (R^2 = 0.35, whereas primary energy is 0.13, n = 14 in 2014), the sector of services space heating with EYSch (R^2 = 0.61, whereas primary energy is 0.46, n =

13 in 2014), and passenger transport with GNI (R^2 = 0.50, whereas primary energy is 0.57, n = 22 in 2014). Thus, final energy as a unique aspect of service provision can be better for studying changes with development in those services. Thus, there are two main observations to make: (i) regarding *n* and (ii) the type of indicators. First, the results around final energy show that being able to use the proposed model depends on the country data available and the shape of the data. Second, even though residential electricity is a good approximation of some services and produces a higher fit than primary energy with some well-being outcomes, this study showed that the service categories of Sustenance, Passenger Transport and the sector of Services Space Heating may be better for studying the correlations with well-being outcomes.

3.4.3 Key results around services

The results of the regression analyses focusing on services are discussed below, focusing on gathering implications from the regressions of the two types of data cross-sections.

Most of the variance of each development indicator may be explained best with two device ownership indicators, however the increased pace of technology adoption is affecting the functional form used to study the links between energy and development. Using the proposed model, most of the variance of each development indicator may be explained best with the indicators of fixed telephone subscriptions and road vehicle ownership, among the other resource chain indicators. This is because such device ownership indicators have the highest R^2 for the maximum *n* cross-section in its large *n* split. The implications of having those two indicators obtain the highest R^2 should be carefully examined. First, because in the case of Communication, two device-related indicators with high *n* were available: fixed telephone and mobile cellular subscriptions. From them, only fixed telephones were significant and had a high R^2, which diminished over time. This implies that the incumbent technology i.e. fixed landlines has followed trends studied in the literature (e.g. primary energy and HDI (Steinberger and Roberts, 2010)), but not the emerging technology, i.e. mobile phones, where access to mobile phones is widespread regardless of the development levels - and shows no correlation with the model proposed. This suggests that the infrastructure needs for building landline connections and the time required to do so brought additional well-being, which does not occur with mobile, because the infrastructure required is less dependant on household connections. Second, there were other service indicators related to devices, e.g. hospital beds that had high *n*, but the shape of the correlation did not fit them. Such observation suggests that at given development levels, the availability of these devices alone cannot be traced to a single development level- and either the study of drivers should be considered or a different model should be tested.

Temporal dynamics exist in the stages of the resource chain, which leads to temporal changes observed in the correlations with development indicators too. Temporal dynamics in correlations between emissions and human development have been discussed in the past (Steinberger and Roberts, 2010). In a subsequent study of the temporal statistical contribution of energy and emission variables on development variables, Steinberger et al. (2020) point out that "a strong correlation between emissions and human development at one point in time does not imply dynamics are coupled over time". The results from the time-series in this study confirm the same, not only for primary energy and emissions, but also for final energy and device ownership indicators. Further, what this study captured is that not only correlation coefficients change over time, but it can be the case that some service indicators have different dynamics and require different functional forms to show those dynamics. An additional temporal dynamic is decoupling between some service and development indicators, where gains in service indicators do not occur alongside gains in development indicators. Correlations of primary energy or total emissions with HDI, income and schooling indicators show decoupling over time. The effect of decoupling has also been observed for energy and development by other academics (Steinberger and Roberts, 2010; Akizu-Gardoki et al., 2018). Such results suggest low emission lifestyles are compatible with increased life expectancy, since a saturation point is reached, confirming a similar finding by Steinberger et al. (2012). The regressions have shown that GNI and AvYSch are the main indicators correlated to total emissions, with GNI showing coupling over time, while AvYSch decouples. This may suggest that increased economic activities and improved education increase well-being at the expense of higher emissions, but over the time period studied, increases in emissions can explain less the increases in schooling levels, but can explain more of the increases in income. The regression results of total emissions also illustrate that high-income countries are found after the saturation point given the less steep curve, and it is known that after saturation is where the highest contributions to global emissions are, as pointed out by Oswald et al. (2020).

3.4.4 Wider implications of the regressions

This study has shown that a semi-logarithmic curve used to study the links between some resource chain and some well-being indicators (e.g. primary energy and life expectancy) is valid only for certain service indicators (e.g. primary energy, embodied emissions, road vehicle ownership). Thus, the inclusion of specific stages of resource transformation has been useful to study whether and how the curves change at each stage, as well as when changes are made to the resource chain, e.g. increasing the diffusion of more efficient devices or changing generation sources as part of the energy transition.

Five key requirements have been identified to obtain significant regression results for further studies of resource chain indicators and well-being. First, since global data is used with varying quality, checking the distribution of each indicator and removing outliers ensures realistic values are included. Second, splitting indicators based on the service in question impacts the correlations, e.g sustenance indicators produce less significant results than transport ones. Third, the model should fit the dynamics of different technologies, e.g. mobile phones. Such dynamics suggest that there are well-being outcomes that will occur at a different pace than the rate of adoption of the technologies. Thus, gains in well-being may be split in two: instant and preserved. The former showing correlations even use of the technology is low and the latter showing correlations only when the adoption of the technology has been incorporated in activities that favour well-being, e.g. personal computers might not be immediately correlated to education. Such instant and preserved gains should be part of the current development rhetoric. Fourth, the service indicators need to include countries at the bottom of the scale so the coefficients reflect the most-accurate relationship between the indicators. Finally, if compound development indicators are used, then the regressions with at least one of their components should be significant.

3.5 Summary of findings

Chapter 3 investigated the nature of the correlations between service provision indicators found at different stages of the resource chain, and different development indicators. The aim is to understand the degree to which service provision is correlated to well-being delivered and how such correlations have changed over time. The regressions undertaken compared pairs of service and development indicators using an OLS regression with a well-known semi-logarithmic form. Generally, the regression curves showed that for constant service-related levels, development is decoupling from the service indicators with significant regression results. The regression results were found to change based on five aspects: the service studied, the form of the curve fitted, the service provision and development indicators in question, the countries considered and specific temporal dynamics. The model used was only able to fit the curve for one service provision indicator per service category when including all the countries available per indicator, except for Residential Thermal Comfort indicators. The regressions showed that significant regressions of compound development indicators depend on having significant regressions with their components too. If more components are significant and have a good curve fit, the fit of the compound indicator is better.

The results allowed for two recommendations on which stage of service provision to focus in each service. First, significant correlations were observed using device ownership indicators in Passenger Transport and Communication. Fixed telephone subscriptions were found to explain 74% of the variation of life expectancy within the sample of countries studied in 2016, yet, over time, the percentage has diminished given the move away from fixed landlines. In turn, the successor technology, i.e. mobile phones did not fit the proposed model, suggesting that both the pace of increasing access to mobile and the pace of development outcomes have changed. The study of the services of Communication is then encouraged from a device ownership perspective, but with an adjusted functional form. Second, final energy is encouraged to be used in the study of Transport and the sector of Services Thermal Comfort with development indicators using the semi-logarithmic model, since these services were able to explain the variance of development indicators. Note that this is beyond household electricity, since transport is included. Another functional form can be also tested to see whether improved R^2 values can be obtained. In some regressions, no significant relationship was found between service indicators and development indicators using the proposed model. For these cases, further study of the dynamics of resource transformation and a different functional form are required. This chapter demonstrated that a focus on service provision using stages of the resource chain may complement energy transition and climate-compatible development studies by showing which indicators to consider in the resource chain, and where to improve data collection efforts or change methodology.

3.5.1 Policy implications

The indicators of resource transformation stages identified in this chapter may facilitate analyses of the resource chain and the social and environmental impacts they have. Additionally, the framework provided by the resource chain may inform policy makers thinking around resource transformations, resource use and their impacts on the population and environment.

The framework and analysis presented in this chapter could be useful for identifying the stages of the resource chain that policies cover and the impact that the policies have had. Additionally, if this analysis were to be applied at a country level, regressions considering relevant groupings and their well-being effects could serve inform policy making so the conditions that lead to correlations with the highest fits are encouraged.

Increased life expectancy resulted compatible with lower total emissions, since a saturation point can be reached where more emissions are not correlated to higher life expectancy.

This chapter also showed that despite the rapid technological development and widespread use of certain devices, the gains to well-being and development are not immediate, given the lag between market penetration of a device, the additional systems built around it and the average well-being gains for the country's population. Policymakers could then identify and quantify instant and preserved well-being gains to analyse the effect of policy interventions.

4

Energy use within a country context

“But if today’s low-income countries are to move from poverty to an incipient affluence... then none of those factors could make a difference without the rising consumption of fuels and electricity: a decoupling of economic growth and energy consumption during early stages of modern economic development would defy the laws of thermodynamics." (p. 350)

- Vaclav Smil, Energy and Civilization: A History

The findings of Chapter 3 showed that the nature of the correlations between service provision and development depends on the service in question, the indicators used, the model used and the countries considered. The results showed that developing country data has important effects in obtaining reliable correlation results, since the inclusion of developing country data tended to increase the steepness of the curves studied. Yet, data availability was a challenge for the study. The results of Chapter 3 also showed that the rapid technology development and market penetration seen for devices such as mobile phones was not correlated to any development indicator using the proposed model. In turn, the incumbent technology was correlated, but at diminishing fits over time. Thus, Chapter 3 demonstrated the need for improved data collection on service provision at country-level and suggested that the dynamics of resource transformation stages, including technology adoption, need to be further studied.

Chapter 2 identified that the understanding of services depends on finding reliable data for end-use devices, including their characteristics, operation and energy use. Such data tends to not be available in developing countries and is hindering analyses on service provision for climate-compatible development. Chapter 2 further identified that local stakeholders should be involved in the creation of models to increase their coherence and obtain actionable results.

To address the gaps in the literature, this chapter aims to demonstrate how to increase the availability of systematic accounting of services in developing countries, in particular, the calculation of useful energy that depends on end-use devices. A single country, Uganda, will be used as an example, which has representative household surveys. These type of surveys have been identified in Chapter 2 as a potential data source for estimating useful energy. As discussed in Chapter 2, global energy use is projected to grow, especially in developing countries. The effect of such growth may lead to high levels of GHG emissions if traditional pathways are followed. Thus, increasing service provision to deliver development can be done, which will also offer opportunities to comply with NDC.

This study will inform whether using available household surveys leads to improved insights on service provision and will include the evaluation of uncertainty. The study will be complemented by comments from local stakeholders to increase the validity of the observations. Such comments were collected during a visit to Uganda at the end of September 2017, where informal interviews were carried out to illustrate the context. The interviews are then considered as qualitative methods, while the calculations using household survey data are quantitative methods.

The parts of the resource chain considered in this chapter are shown in figure 4.1, along the research question.

RQ2: *What insights on local service delivery may be drawn from harnessing available developing country data?*

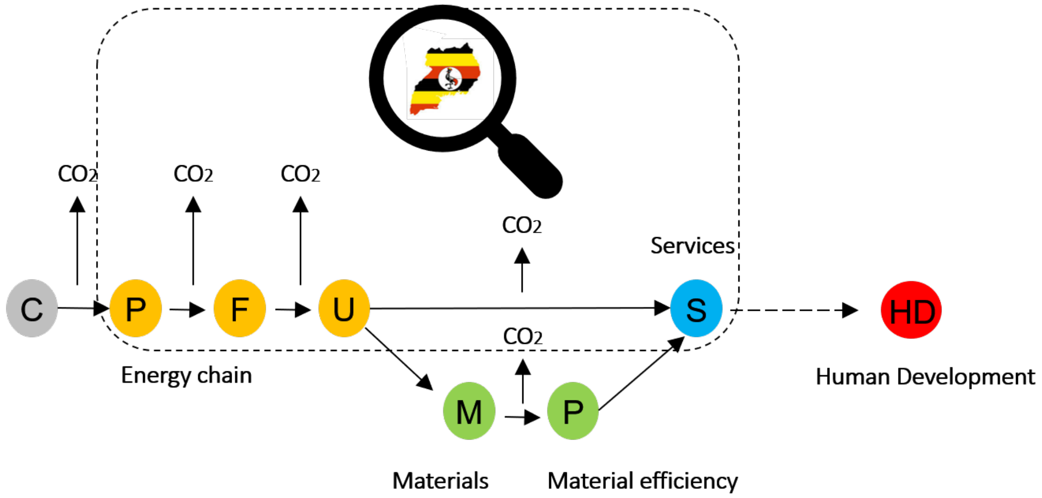


Fig. 4.1 Resource chain to provide services and the parts considered in this chapter. The dashed box shows which resource transformations this chapter focuses on from primary to services and the magnifying glass shows it is a study focused on Uganda.

This chapter is structured as follows: Section 4.1 introduces the country selected for the study. Section 4.2 presents the data gathered for this study and the methods used to analyse such data. Section 4.3 contains the results and discussion, and makes comparisons with the literature. Finally, section 4.4 summarises findings and discusses policy implications.

4.1 Introduction to Uganda's context

Uganda is an African developing nation, with growing energy demand and scarce detailed energy use data. Uganda is a country that gained independence from the United Kingdom in 1962 and whose post-colonial history includes a dictatorship and military regime, ending in 1979, followed by a president whose tenure began in 1986 and is still in power to this day. Currently, Uganda is among the poorest countries of the world, with 37.7% of the population living on less than \$ 1.25 a day (Ugandan Ministry of Energy and Mineral Development, 2015). The energy system in Uganda, including the development of electrification infrastructure, has been partially hindered by the lack of long-term political stability, and high levels of poverty.

In 2016, only 26.7% of the Ugandan population had access to electricity; this is lower than other East African Community members, such as Kenya (56%) and Tanzania (32.8%) (World Bank, 2018). This means, that of the approximately 7 million households in Uganda, 618,000 in urban areas and 4.85 million in rural areas are still to receive access to electricity (Ugandan Ministry of Energy and Mineral Development, 2015). Furthermore, energy derived from unsustainable biomass sources, such as charcoal and firewood, accounts for nearly 90% of the total energy demand (Rebel, 2015).

Wealthier households, mainly in urban areas in Uganda, show increased levels of electricity use for lighting and cooking (Rahut, Behera, Ali and Marenya, 2017*b*). Yet, even when households have access to electricity they are still likely to use biomass sources for cooking (Rahut et al., 2016). Furthermore, electricity access is often intermittent and unreliable, meaning households tend to rely on biomass sources for many routine household activities (Rahut, Behera, Ali and Marenya, 2017*b*).

The highest estimated power demand for 2030 is from the large industrial sector, according to the Ugandan Ministry of Energy and Mineral Development (2015), although it is suggested that the domestic sector will be almost as large. Furthermore, the Ugandan Ministry of Energy and Mineral Development expected the electricity per capita consumption to more than double between 2012 and 2020 from 84 kWh in 2012 to 180 kWh by 2020.

The Ugandan government has committed to reducing GHG emissions through a "series of policies and measures in the energy supply, forestry and wetland sectors" (Ministry of Water and Environment, 2015). These are estimated to reduce carbon dioxide equivalent emissions by approximately 22% from the business-as-usual (BAU) estimates of 77.3 million tons ($MtCO_{2eq}$/yr) in 2030. Proposed mitigation measures in the energy system include: a four-fold increase in electricity generation (from 729 MW to 3,200 MW), which has the potential to offset wood and charcoal burning; energy efficiency in hospital buildings; "Integrated Sustainable Energy Solutions" in off-grid area schools; energy efficient building codes for construction and renovation; energy efficient cooking stoves and induction cookers; and fuel efficiency standards for vehicles. However, the individual mitigation potential for each measure is in almost all cases quoted "unknown", leading to some uncertainty about achieving the overall target. Articulating the mitigation potential more accurately would require a more detailed understanding of how energy is used by consumers and for what purposes, and improved tools to predict the impact of changes in the upstream energy system (e.g. biomass to electricity) on end-use energy demand.

In response to the lack of end-use energy data, this chapter focuses on analysing energy uses in Ugandan households, using bottom-up analyses of practices derived from the existing national household surveys. The study focuses on energy used for cooking and lighting and examines explanatory variables such as the type of settlement (urban or rural), the level of household expenditure, fuel types and end-use energy devices.

4.2 Data and Methods

This study presents a mixed-methods approach, where quantitative and qualitative methods are used. The qualitative methods include performing semi-structured interviews with relevant stakeholders in Uganda and the UK to inform the context of the study, and are presented in section 4.2.1. The quantitative methods include performing a bottom-up assessment of energy uses and practices in Ugandan households, which are presented in section 4.2.2.

4.2.1 Qualitative data and methods

The qualitative methods of this research refer to semi-structured interviews with relevant stakeholders that provide information regarding the context. The interviews are organised with stakeholders both in Uganda and the UK. Seven experts are consulted who work in the areas of government, energy planning, solar energy and academia. The comments of each expert on their experiences and insights are gathered, and follow-up questions are asked to investigate how service provision occurs, which strategies are followed to deliver services, and which efforts they consider to be required to improve service provision. The interview protocol is described in Appendix B.

Figure 4.2 shows the organisations included in the interviews.

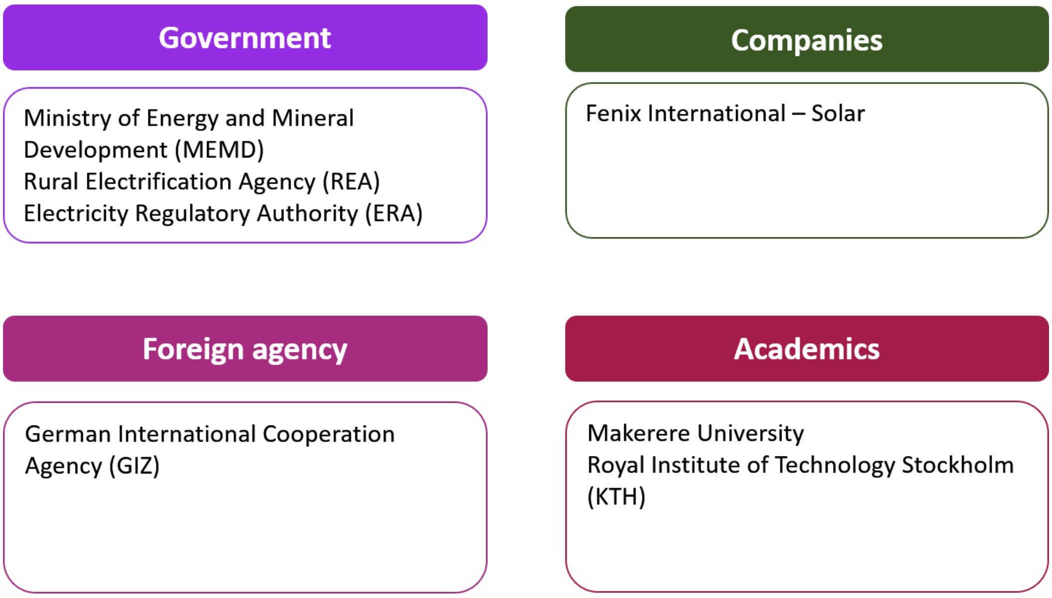


Fig. 4.2 Organisations approached for interviews.

4.2.2 Quantitative data and methods

Quantitative data

Household survey data from 2009 to 2016 are used, focusing on the provision of sustenance and illumination services. Three main types of data sources are used including National Panel Surveys (NPS) for the years 2009 to 2016 (Uganda Bureau of Statistics, 2010, 2011, 2012, 2014, 2016); a 2010 Ugandan food survey by Harvest Plus (Hotz et al., 2010); and the 2015 Ugandan National Charcoal Survey (Rebel International, 2015).

The NPS gathers representative household panel data from across Uganda on a rolling basis throughout the calendar-equivalent year (to avoid seasonal bias). The household data can be aggregated into monthly expenditure deciles per adult equivalent (ad-eq), which accounts for the average mix of adults and children per household (for details on the calculation, refer to section B.0.5 in Appendix B) and by settlement type (rural or urban). Table 4.1 shows both the mean household expenditure and number of households by settlement type for the 2013-2014 wave. It is important to note that of the sample size (n) of 3,200 households surveyed in that wave, only 1,948 provide sufficient expenditure data to be included in the analysis.

Table 4.1 Monthly expenditure deciles per adult equivalent in 2013 Ugandan Shillings (UGX) and number of households per decile and by settlement type.

	Household expenditure (decile per ad-eq)				*Sample size (n)*		
Decile	*Mean*	*Std*	*Min*	*Max*	*Total*	*Rural*	*Urban*
0	57,201	19,295	10,667	86,625	195	172	22
1	106,099	11,972	86,892	128,523	195	173	23
2	150,965	12,090	128,592	172,519	194	164	30
3	198,321	15,660	172,638	226,917	195	158	37
4	256,060	16,823	227,700	285,702	195	157	38
5	319,966	20,851	285,833	361,111	194	143	51
6	412,281	33,870	362,946	475,153	195	146	49
7	561,761	52,381	475,207	657,885	194	123	71
8	809,718	122,536	658,000	1,076 104	195	116	79
9	2,036,170	1,683,117	1,077,214	16,223,578	195	59	136

Quantitative methods

The quantitative methods of this study include the following: the household surveys are used to extract the amounts and types of energy sources used and their efficiencies. Then, the total final energy used and useful energy for cooking and lighting are calculated by settlement type and expenditure deciles. Finally, the total carbon dioxide equivalent (CO_2) emissions related to the total final energy values are calculated.

Data extraction for calculating final and useful energy, and emissions

From the sample size of 1,948 households that provided useful expenditure data for further calculations, a smaller fraction (n = 1,627) provides sufficient information to allow for the calculation of household final energy use to be made. The difference is from households who either chose not to answer the energy section of the survey (unit non-response) or failed to provide sufficient data to calculate final energy use (item non-responses).

Table 4.2 shows the households who report specific fuel use, as a fraction of the total households who indicate generic energy use, e.g. from all the households that said they used charcoal for cooking, 98% reported quantities. No final energy use data is provided in the survey for the fuels of Crop Residue, Dung and Solar, and few households (11%) reported Firewood quantities.

Table 4.2 Percentage of households that report weight or volume of energy sources from the households that use such source for stated uses.

Fuel name	*Used generally*	*Cooking*	*Lighting*	*Heating*
Charcoal	98	98	75	100
Crop Residue	0	0	0	0
Dung	0	0	0	0
Electricity	42	42	42	21
Firewood	11	11	3	7
Kerosene	100	100	100	100
LPG	100	100	0	100
Solar	0	0	0	0

Final energy calculation

Households in the survey reported end-use energy device ownership and use (i.e. cooking stoves, appliances), indicated the purpose of energy source use (cooking, lighting or heating) and estimated the quantity of energy sources purchased or used. The fuel quantities are not measured in consistent energy units, but instead the common unit of purchase (e.g. kilograms, litres, sacks, tins, heaps, bundles).

Table 4.3 shows the conversion factors specific to Uganda to convert purchased energy source quantities into standardised mass and energy units. The reported units of purchase are first converted to units of kilograms (kg) using Ugandan specific estimates from literature, followed by a conversion to joules (J) using standard fuel calorific values and densities. The National Charcoal Survey (Rebel, 2015) is used for calculating the energy equivalents of purchased charcoal measures by region.

Table 4.3 Conversion factors from mass and volume of energy sources to energy units.

Code	*Unit*	*Charcoal*	*Firewood*	*Kerosene*	*LPG*	*Comments*
1	kilogram (kg)	1	1	1	1	No conversion needed
3	litre (l)	0.4		0.8		Kerosene density: 0.8 g/cm^3
9	Sack (120kg)	120	120	120		Sack mass defined in the survey
10	Sack (100kg)	100	100	100		
11	Sack (80kg)	80	80	80		
12	Sack (50kg)	50	50	50		
13	Sack (unspecified)	87.5	87.5	87.5		Assumed
21	Tin - 5L	2				Volume defined in the survey
96	Bundle - big		11.6	50		Assumed values. Firewood is 30% more than medium bundle
97	Bundle - medium		8.9	33		Average reported in National Charcoal Survey (Rebel International, 2015)
98	Bundle -small		6.2	25		Assumed values. Firewood is 30% less than medium bundle
123	Akendo - big	40		40		From Hotz et al. (2010)
124	Akendo - medium	20.8		20.8		
125	Akendo - small	10.7		10.7		
133	Sadolin tin - 3L	1.2				Volume defined for charcoal in the survey
NA	Megajoule (MJ/kg)	29.3–30.9	19.5	43.3	48.0	Calorific values. Charcoal values include regional variations (see section B.0.3 in Appendix B)

Table 4.4 shows the results of mean final energy use (in Megajoules per month per ad-eq) and the mean number of energy sources per decile (which represents the mix available), split by settlement type (rural or urban) for the households in each expenditure decile. Data from households which did not report specific amounts of energy sources used are removed from this part of the study onward.

Table 4.4 Sample size per expenditure decile where final energy could be calculated, average final energy (in Megajoules per month per adult-equivalent) and average number of fuels measured.

		Mean final energy (MJ/mo ad-eq)		*Mean energy sources (n)*	
Decile	*Households (n)*	*Rural*	*Urban*	*Rural*	*Urban*
0	136	27.10	38.16	1.06	1.15
1	146	26.93	48.50	1.07	1.11
2	167	46.69	186.80	1.09	1.23
3	159	69.39	285.58	1.17	1.69
4	165	95.42	235.80	1.14	1.38
5	161	105.33	383.98	1.20	1.49
6	167	164.86	359.97	1.21	1.61
7	166	278.42	374.74	1.35	1.72
8	180	304.23	585.97	1.48	1.83
9	179	494.70	661.09	1.54	1.87

The sampling error in each decile is evaluated using equation 4.1, enabling the uncertainty in the final energy values to be shown. The sampling error refers to the "part of the difference between a population value and an estimate thereof, derived from a random sample, which is due to the fact that only a sample of values is observed" (OECD, 2005).

$$\text{Error}_{decile} = \frac{\sigma_{decile}}{\sqrt{n_{decile}}} \tag{4.1}$$

Where σ_{decile} refers to the weighted standard deviation, and n_{decile} refers to the number of samples of households that report Final energy.

Useful energy of end-use devices

The useful energy (e.g. light, heat) delivered to consumers can be found by multiplying the final energy used by end-use devices and the energy conversion efficiency of each device, as shown in equation 4.2.

$$U = F\,\eta \tag{4.2}$$

where U is useful energy, F is final energy and η refers to device efficiency.

For this study, the energy values that represented the use of cooking were the only ones considered (so if the same source was used for both cooking and lighting, those values were removed), to not add more uncertainty associated with the split of energy sources for different end-uses. This was deemed appropriate given that the main energy sources used for cooking and lighting tend to be quite different, as shown in figure 4.5.

Considerable uncertainty exists in both the final energy and end-use device efficiency values, therefore distributions of useful energy (U) values are found using a Monte Carlo simulation, which takes into account this uncertainty. The step of estimating uncertainty in this breakdown of households is novel; providing device efficiency distributions aligned to expenditure deciles reveals which devices in each decile have room for improvement.

The NPS contains information about the types of cooking stove used in each household. Each device type is paired to a specific fuel allowing estimates of the thermal efficiency for each stove type. The efficiencies were obtained from the relevant stoves in the Clean Cooking Alliance (United Nations Foundation, 2019) database. Kerosene stoves values come from (Center for Energy Studies, 2001). The values are shown in table 4.5. Equation 4.3) sums the useful energy across all types of cooking stoves, fuel types and efficiencies.

$$U_{eu,hh_j} = \sum F_{dev_k,hh_j}\ \eta_{dev_k} \tag{4.3}$$

Where U_{eu,hh_j} is the useful energy by end-use for household j; F_{dev_k,hh_j} is the final energy input to each device, corresponding to the same end-use in household j and η_{dev_k} is the end-use device energy conversion efficiency.

A normal distribution of thermal efficiencies per household is obtained using a Monte Carlo approach.

Table 4.5 Stove thermal efficiencies (%) used according to the energy source they correspond to.

		Efficiency			
Fuel name	*Stove name*	*Mean*	*Min*	*Max*	*Std*
Firewood	Wood / Sawdust Burning	25.62	19.89	31.31	2.85
Firewood	Efficient Wood Burning	30.75	23.87	37.57	2.85
Firewood	Open fire	12.81	9.95	15.65	2.85
Kerosene	Kerosene	38.21	37.80	38.62	0.21
LPG	LPG	40.00	35.00	44.90	2.47
Charcoal	Charcoal	30.92	25.79	35.96	2.54
Electricity	Electric	68.70	60.50	84.50	6.00

Device efficiencies are then aggregated across each decile using equation 4.4) and the distribution for useful energy is visualised using using error bars.

$$U_{eu,dec_i} = \sum U_{hh_j,dec_i} \tag{4.4}$$

where U_{eu,dec_i} is the useful energy for end-use in decile i and U_{hh_j,dec_i} is the useful energy for household j in decile i.

The device efficiencies are assumed to have a normal distribution with a standard deviation calculated as shown in equation 4.5.

$$\sigma_{device} = \frac{\eta_{max} - \eta_{min}}{4} \tag{4.5}$$

where σ is the standard deviation and η_{max} and η_{min} are they maximum and minimum device efficiencies.

Emissions

The CO_2 equivalent emissions (C) for each household are calculated as per equation 4.6. Then, using C and the household survey weights, the average weights of emissions are calculated to compare the emissions per decile and settlement type. The emission values consider direct burning of the different energy sources and are taken as the gross CO_2 equivalent emissions. Emissions from electricity are calculated considering the average electricity emissions for Africa, excluding losses from transmission and distribution, since no data for Uganda was available. The emissions obtained with this approach will likely have higher values than Uganda's electricity emissions, since parts of the region rely on coal (e.g. South Africa) or natural gas (e.g. north Africa) (IEA, 2019*a*), while Uganda relies on 80% hydropower for electricity generation capacity (USAID, 2020). However, since the electricity access for the population was only 27% in 2016 (World Bank, 2016), the error in the estimation will have a small effect.

$$C = \sum S\, f \tag{4.6}$$

Where C refers to CO_2 equivalent emissions, S refers to the energy source's reported mass or energy in the case of electricity (in kWh) and f are the GHG conversion factors from table 4.6.

Table 4.6 Emission factors for kg CO_2 eq used. Data taken from the UK Government GHG Conversion Factors for Company Reporting 2019. Scope 1 used for all fuels except for electricity, where Scope 3 was used as the category of 'WTT - UK & Overseas Electricity'.

Fuel name	*Category name*	*Emission factor*	*unit*
Firewood	Wood logs	63.84	kgCO_2/tonne
Kerosene	Burning oil	3165.36	kgCO_2/tonne
LPG	LPG	2936.86	kgCO_2/tonne
Charcoal	Coal (domestic)	2744.72	kgCO_2/tonne
Electricity	Electricity: Africa (average)	0.08	kgCO_2/kWh

4.3 Results and discussion

The results are organised as follows: insights from the interviews are shown in section 4.3.1, the share of households using given energy sources are shown in section 4.3.2, final energy use in section 4.3.3, useful energy for cooking in section 4.3.4, and finally the resulting emissions are shown in section 4.3.5.

The results of the study provided for the energy uses of cooking and lighting, and organised by settlement type and expenditure deciles.

4.3.1 Interview insights on Uganda

The interviews in Uganda were carried out at the end of September 2017. The insights gained from the experts consulted have been divided into relevant categories and are shown below:

- **Various energy end-uses**:
  - Cooling is done at commercial scale, not residential.
  - Most households consume fresh food and use almost no refrigeration.
  - There is no public transport, it is all run privately.
  - For lighting using off-grid solutions, a white bright light is preferred by customers.
- **Infrastructure**:
  - For electricity access, off-grid and mini-grids are used when there is low or unreliable electricity access. The government invests in major electricity generation projects (above 100 MW).

  - There is foreign investment behind some of the infrastructure improvements such as roads and street lights.

- **Businesses and productive uses of energy**: There is some interest in focusing on energy for productive uses that benefits household economies (also confirmed by (Brüderle et al., 2011; Hirmer and Guthrie, 2017)).
  - Specific business models and products are used in solar home systems. Solar product shops are abundant in Kampala and its surroundings.
  - The language diversity in Uganda presents challenges for international businesses.
  - Although there's encouragement to switch to 'cleaner' fuels, night salespeople are using mainly kerosene lamps to light their stands and only some have solar lanterns.
  - Mobile money has enabled new activities, such as money transfers, keeping savings and making payments.
- **Socioeconomic conditions**: Education is considered valuable, so it is common that a high portion of household's income is used for private education. This occurs despite the free primary education.

4.3.2 Share of households using given energy sources

Reliance of households on a range of energy sources is commonplace in Uganda. Figure 4.3 shows this diversity in energy sources as the share of households recording the use of energy sources, for the NPS waves between 2009 and 2016. The results show, over time, marginal reductions in households using kerosene, but increases in the use of solar and biomass. The share of households with access to electricity remains low throughout, at approximately 10% of households, which surprisingly, is lower than the use of batteries (although the energy delivered via these energy sources might differ). Overall, the changes over the six-year period are minimal, indicating the difficulties on moving households to new and 'improved' energy sources, despite the ongoing policy and development efforts in Uganda.

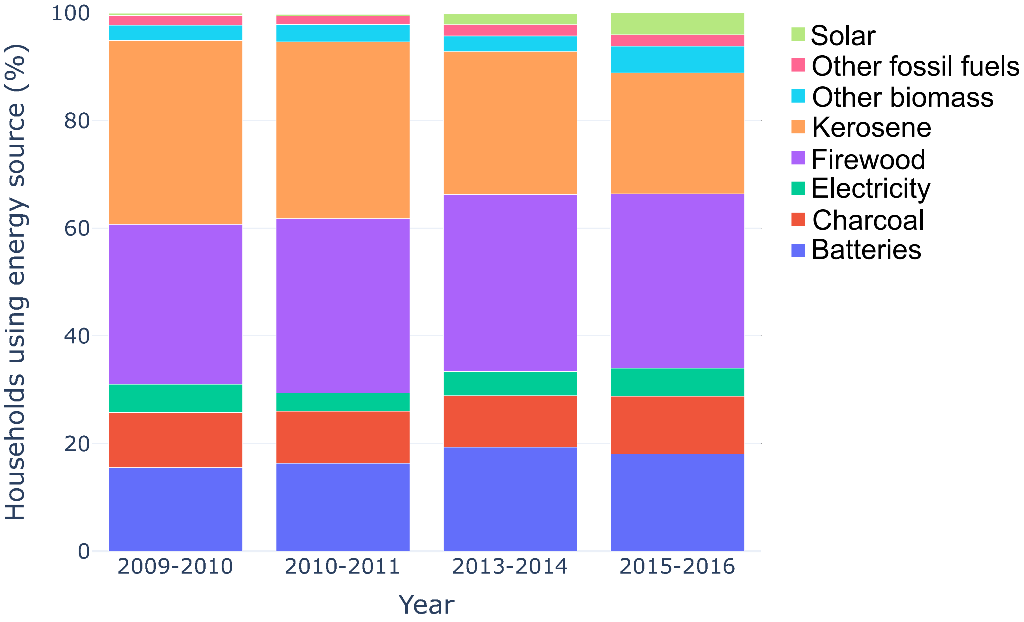
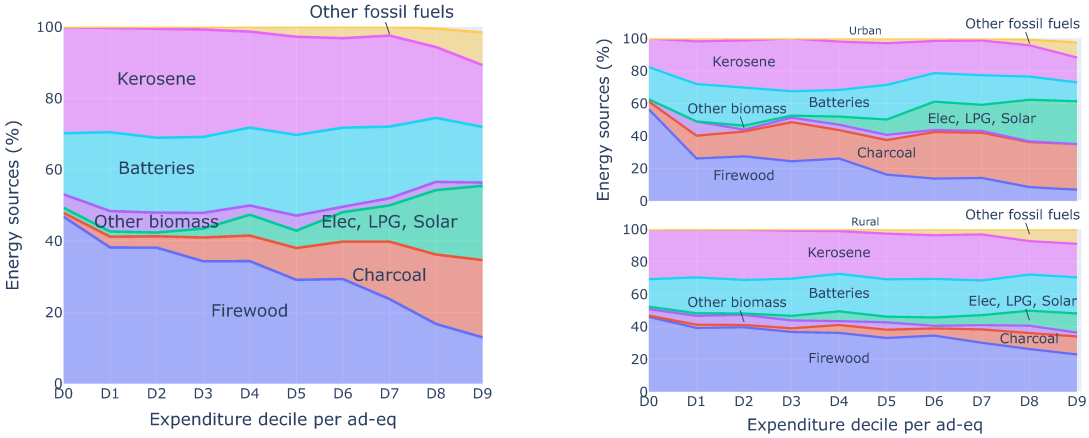


Fig. 4.3 Share of Ugandan households recording the use of given energy sources in the NPS conducted between 2009 and 2016.

Figure 4.4 explores the households shares in energy sources in more detail, comparing the reported shares of energy sources against expenditure deciles for the 2013-2014 NPS. It is clear, that while the share of energy sources remain relatively static with time, there is significant variance across different household spending levels. Figure (a) confirms common wisdom, that as expenditure grows, the share of households using of firewood decreases, with much of the decline being displaced with charcoal, particularly in urban settlements (b). Reductions in kerosene use (for lighting) and battery use can also be seen, displaced in some part by solar and other fossil fuels.

The use of given energy sources between settlement types remains remarkably similar for lower expenditure households (deciles D0 to D4), apart from the switch of firewood to charcoal in urban settlements. More divergence is seen for higher expenditure households (above decile D5) in urban settlements, where the penetration levels of electricity, LPG and solar increase as expenditure grows.

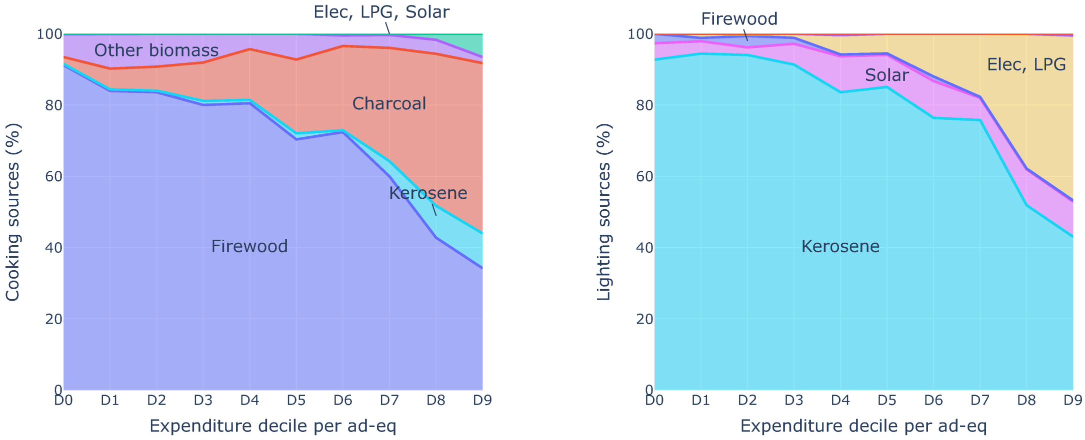
Figure 4.5 shows the trends of energy sources used for cooking and lighting across the household expenditure deciles. For cooking (a), a reduction in share of households using firewood is observed, by almost 60% across the deciles, with firewood being substituted by charcoal and some kerosene at higher expenditures. Lighting (b), on the other hand, is provided almost exclusively by kerosene at lower expenditure deciles (D0 to D3), but is rapidly displaced by electricity and LPG (dropping by about 50%) expenditure increases. The share of households using solar for lighting remains relatively constant, and at a low fraction (less than 10%), across all expenditure deciles. In terms of transitions, the switch to solar seems mainly done in rural settlements, whereas the switch to electricity and LPG is mainly for urban settlements.



(a) Total

(b) By settlement type

Fig. 4.4 Share of Ugandan households recording the use of given energy sources against deciles of expenditure shares per adult equivalent in 2013-2014: (a) overall, (b) by settlement type, urban (top) and rural (bottom)



(a) Cooking

(b) Lighting

Fig. 4.5 Cooking and lighting energy source shares and deciles of expenditure shares per adult equivalent (ad-eq) in Ugandan households in 2013 for cooking (a) and lighting (b).

The observed mix of energy sources used in Uganda contributes to the body of empirical evidence that has observed that fuel stacking tends to occur as country energy systems change, instead of adopting new practices entirely (Masera et al., 2000; Ruiz-Mercado and Masera, 2015; Choumert-Nkolo et al., 2019). The households in higher expenditure deciles (D8-D9), with higher electricity access, not only still showed reliance on fuel stacking, but also showed a higher number of energy sources used overall (refer to table 4.4). This result not only confirms the theory of fuel stacking, it also implies that unless reliable energy access and changes in practices are implemented, the accumulation of materials or devices is only bound to increase, especially in urban settlements. This is due to the higher availability of energy sources in urban settlements and the easiness to collect, purchase or produce biomass-related sources in rural settlements. Peng and Pan (2010) also observed this fuel stacking behaviour in rural China, where even when there is electricity access, if it is intermittent, the households may need to rely on other fuels.

Similarities between the energy sources used in Uganda and other countries in the region are observed. The changing cooking sources from firewood towards charcoal and the higher adoption of modern lighting fuels compared to cooking fuels has also been observed for Tanzania (Choumert-Nkolo et al., 2019). Compared to other African countries, the low electricity access in Uganda, also leads to lesser social payoffs, as identified by Bahadur et al. (2017).

4.3.3 Final energy use

Final energy is calculated for all energy sources, where measurable information was provided in the NPS (refer to table 4.2).

Figure 4.6 shows the average final energy for each expenditure decile, by rural and urban settlement types, including sampling errors. Final energy use is shown to grow with increasing household expenditure, as expected, at first slowly for lower expenditure levels (D0 to D5 for rural and D0 to D2 for urban) and then more rapidly. Urban households use more final energy across all household expenditure deciles, suggesting that access to energy (and not just income) drives final energy use. In urban settlements, higher middle-income households (D5-D7) show a similar energy use trend, which only increases significantly in the last two deciles (D8 and D9). Urban deciles D8 and D9 show a higher energy use than the rest of the deciles and, interestingly, only D9 households reported electricity values, which means D8 households cover their similar energy needs in other ways.

Inconsistencies in the trend for urban settlements are due to the reported values. For instance, D4 seems lower than the trend would have suggested. The reason is that a household reported using low kerosene quantities used for cooking, compared to energy derived from biomass reported in that same decile, thus bringing the average down. In general, the sampling error is high if sample size is low or if there is a high variance within the reported energy, which implies than any inaccurate household report has a higher effect on the calculated average. Therefore, calculating the sampling error is informative.

At lower deciles, the information on household energy has lower sampling error in rural settlements, because many households are found there (having a high n). These households report information on some energy use, but not all, particularly not many report firewood quantities, as previously mentioned. This means that the real energy use is expected to be higher in some of the lower deciles. However, since the under-reporting of firewood is widespread, it is considered a consistent error, and conclusions may be drawn.

The results in this section showed that not only income, but also access to energy and type of settlement are drivers of final energy use. This is in line with observations from Bahadur et al. (2017), who concludes that, besides those drivers, education is also an electricity use driver in Uganda and other African countries (Ethiopia, Tanzania and Malawi).

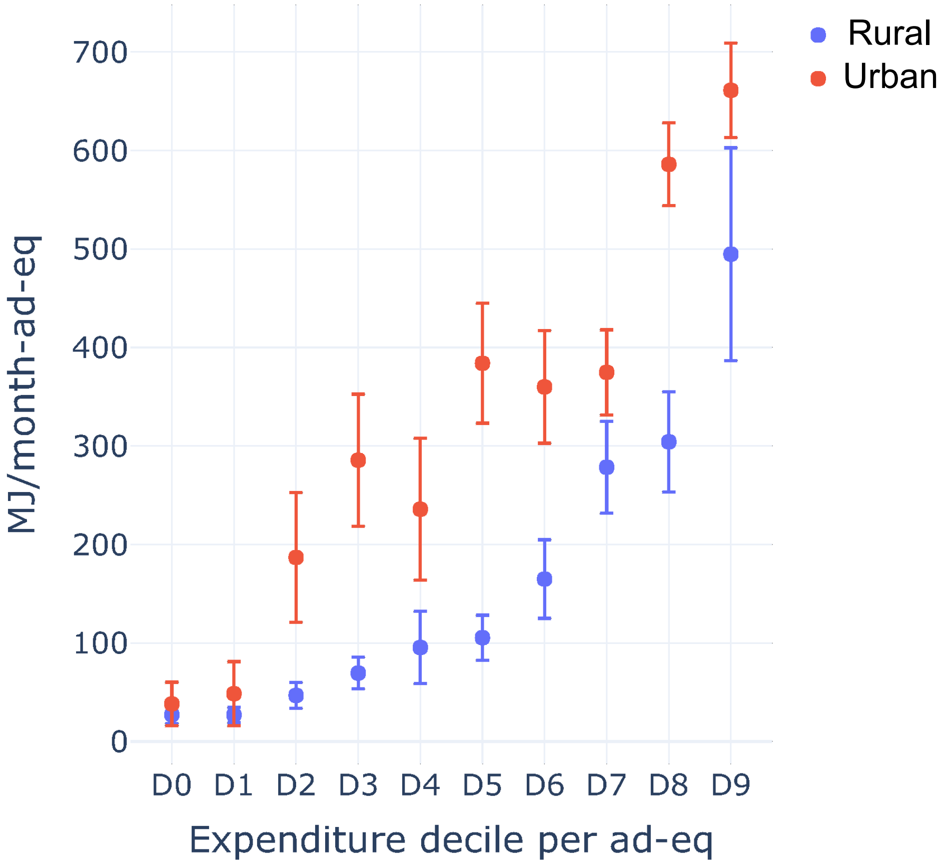


Fig. 4.6 Total final energy (including all energy sources available) per adult equivalent (ad-eq) and deciles of household expenditure per adult equivalent split by settlement type, including sampling error shown as error bars. Values for 2013-2014 survey.

4.3.4 Useful energy for cooking

Figure 4.7 shows a comparison of final and useful energy, including the average efficiency for each decile. The average efficiency increases slightly at higher deciles, particularly in urban settlements, whereas useful energy grows more with expenditure in rural settlements. Increased useful energy is due to a combination of higher energy used and higher stove efficiencies. On average, households tend to use about the same useful energy for cooking after reaching D6 in rural and D4 in urban settlements.

As predicted, those deciles where the upwards trend for useful energy seems higher than normal are due to higher final energy being used (e.g. D0, D2, D4 urban). Low deciles show a higher reliance on inefficient firewood, whereas higher deciles increasingly use more efficient sources. After D6 in rural settlements and D3 in urban ones is when a higher phasing-out of firewood is observed, judging by the higher average efficiency values. Interestingly, high deciles still show similar percentages of final/useful energy (around 30%), which means that even the wealthiest people are not adopting the most efficient cooking techniques - or are not measuring the use of those more efficient devices.

The findings of the lack of efficient stove use even in wealthier households can be attributed partially to the availability of stoves for purchase. SNV Uganda (2014) discuss that cooking stoves in Uganda can be purchased in the common retail outlets, or the less-common open markets or exhibitions. Improved stoves are found in open-markets or exhibitions and thus have a lower share of total purchases (SNV Uganda, 2014).

Local practices are another reason why wealthier households do not use more efficient stoves. Garland et al. (2015) observe that households that have an improved cooking fuel (in their case LPG) keep using some charcoal, which they discuss is related to local practices or preferences. Masera et al. (2000) further explain that apart from the financial constraints to switch stoves, the local cooking habits need to be examined. The results in this study also call for such local habits and practices to be understood. The case of lighting can be used as an example, as reflected by the faster switch to improved lighting sources and the interview insights from the off-grid lighting sector.

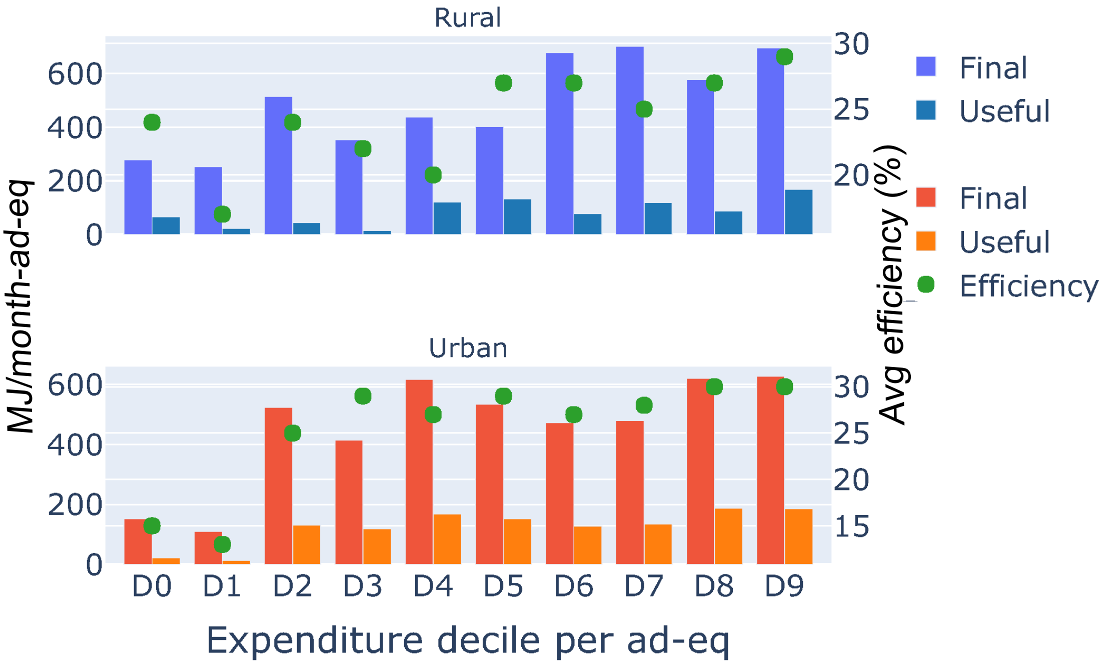


Fig. 4.7 Comparison of final and useful energy for cooking (left y-axis) with their respective average efficiencies (right y-axis) and deciles of expenditure per adult equivalent by settlement type. Values for 2013-2014 survey.

4.3.5 Emission impacts

Figure 4.8 shows the average emissions for each expenditure decile associated with final energy. As households get richer, their average emissions linked to final energy increases, being urban emissions usually over double those for rural. This suggests that households moving to higher expenditure deciles and urbanising will lead to higher national emissions from the household sector.

The difference however between the highest urban deciles (D8 and D9) are almost double the emissions of the middle-income urban households (D5-D7), and three times or over the emissions in most rural households (D7 and below). This suggests that fuel stacking and urbanisation have the consequence of increasing emissions, since there are more energy sources available as households become wealthier. The literature has suggested that the effect of urbanisation on emissions is significant, yet heterogeneous, with income levels being a determinant of general trends (Poumanyvong and Kaneko, 2010; Li and Lin, 2015; Salahuddin et al., 2019). Thus, the results concur with an observation by Li and Lin (2015), where urbanisation in middle-/low-income and high-income groups increase energy consumption and emissions. Further, Li and Lin (2015) identifies that urbanisation in middle- and high-income groups limits the growth of emissions, while not affecting energy consumption. This suggests that, if the trends in Uganda are consistent with Li and Lin (2015), Uganda has an opportunity to move away from the trend identified in this study if strategies are devised for different income levels.

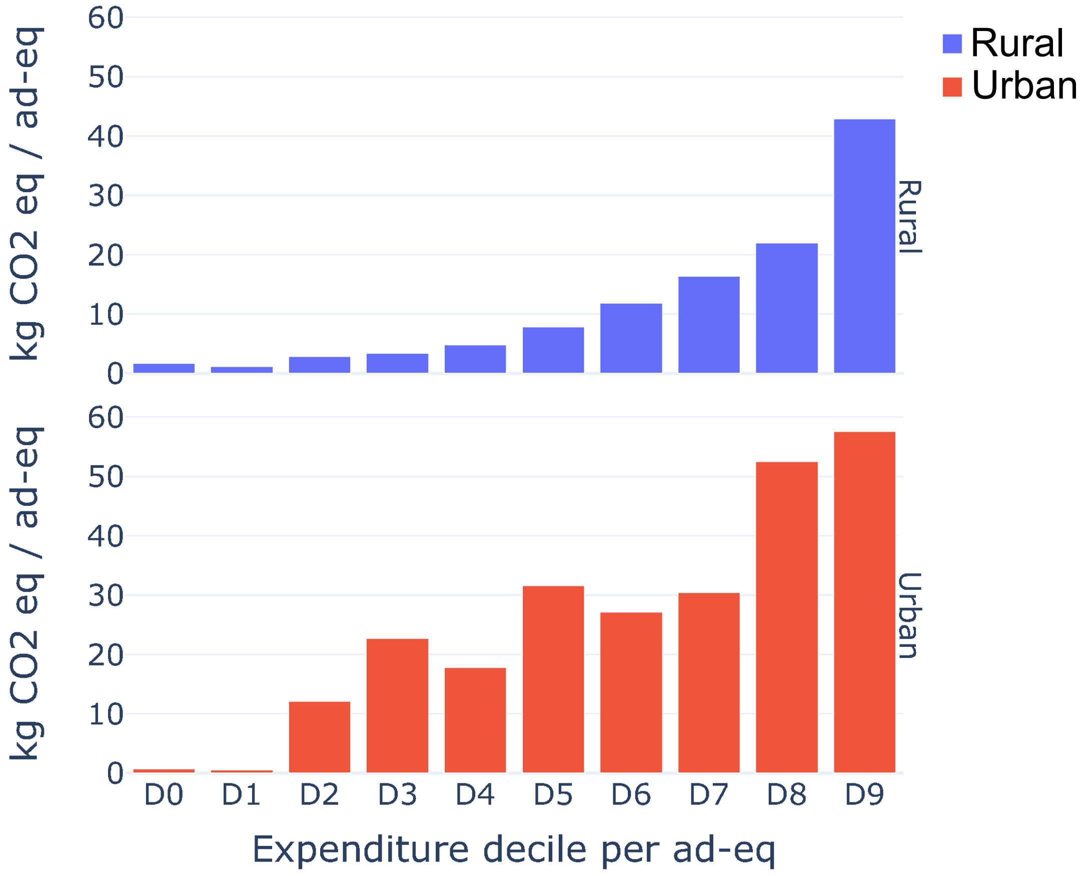


Fig. 4.8 Mean CO_2 equivalent emissions per adult equivalent (ad-eq) by household deciles of expenditure per adult equivalent by settlement type in 2013.

4.4 Summary of findings

This chapter presents a bottom-up analysis of energy use in Ugandan households, combined with semi-structured stakeholder interviews to gather insights on the context. The qualitative part included interviewing seven stakeholders working in varied areas, from government to academia. The quantitative part included examining changes in energy sources used by Ugandan households from 2009 to 2016, using data from the 2009 to 2016 National Panel Surveys (NPS), the 2010 Harvest Plus food survey, and the 2015 Ugandan National Charcoal Survey. The interviews collected insights from seven experts in areas ranging from academia to local government. The analysis examined changes in energy sources and energy use patterns from 2009 to 2016, aggregated by urban and rural settlements and household expenditure deciles. Final energy and emissions were calculated aggregated by urban and rural settlements and household expenditure deciles. Final to useful energy were calculated for the provision of cooking using a detailed methodology to estimate efficiencies and their uncertainty.

The results showed that lighting has transitioned to improved energy sources before cooking, which remains reliant on biomass. Fuel stacking resulted common in Uganda, especially in wealthier households. Fuel stacking is contributing to the slow transition away from traditional energy sources, and exacerbating emission increases with urbanisation. Other factors that contribute to fuel stacking and the slow transition are the availability of energy sources and devices, income and local practices. These factors also contributed to slums having lower cooking stove efficiencies than rural households in low expenditure deciles. The insights from the interviews showed that changes are occurring in service provision regarding lighting, transport infrastructure and innovations related to mobiles, which are facing local challenges, such as the language diversity.

4.4.1 Key takeaways from the study

The key takeaways from the study considering the results obtained are the following:

The speed of energy transitions in Uganda depends on local practices for specific services, with innovations and investments bringing changes. Lighting shows more signs of a transition than cooking. The interviews also revealed sustenance does not rely on refrigeration. Slow energy transitions away from traditional biomass uses were observed. In specific end-uses, there was a clearer variation on the time taken to achieve transitions. Lighting showed a quicker transition away from kerosene and into electricity and solar, although that transition still fails to reach the lower rural deciles. On the other hand, cooking remained reliant on biomass, with increasing amounts of charcoal used at higher deciles, mostly in urban settlements. The interviews revealed that cooking relies on the use of fresh food with little refrigeration use, and that innovations such as mobile money and investments in roads are paving the way for practice changes.

Fuel stacking contributes to the slow pace of energy transitions and increased emissions as Uganda urbanises, with wealthier households showing the most stacking. Higher fuel stacking was observed at higher expenditure deciles (D8-D9), especially in urban households and even when electricity was available. Yet, both lower and upper deciles relying on biomass have potential for increasing device efficiencies. Several other factors were identified that contribute to the slow transition: availability of energy sources and end-use devices (which depend on collection, production or purchases), income or expenditure, and local practices and habits. There are then opportunities to devise strategies that limit emissions, e.g. for different income levels.

Ugandan households are not adopting the most efficient cooking techniques, not even the wealthiest, while slums have lower efficiencies than low rural deciles. Useful energy for cooking increased as household expenditure increased, both because more energy was used, but also because more charcoal stoves were used. Urban settlements showed higher energy use and similar energy use levels for cooking from medium-expenditure deciles onward, whereas energy use increased more steeply with expenditure in rural settlements. Urban settlements tended to have similar values of useful energy from approximately the third decile onward. The preferred cooking fuels were biomass-based, which have low efficiencies pushing down the useful energy. Even high deciles showed do not use efficient cooking devices. Slum areas and similar presented worse conditions in terms of useful energy and efficiency than their expenditure counterparts in rural areas. This is likely due to the easiness to collect firewood in rural areas.

4.4.2 Policy implications

Historically, energy transitions imply finding energy sources that maximise energy delivery while reducing reliance on muscle power and biomass. Energy transitions can be aided by creating policies that enable, encourage or regulate them. In the case presented in this chapter, the changes in shares of energy sources used over the six-year period studied were minimal, indicating the difficulties of moving households to new and ‘improved’ energy sources, despite the ongoing policy and development efforts.

In the case of Uganda, the energy transition has started to occur mostly in the capital and some key regions, however biomass for cooking is widely used despite household’s expenditure levels. The transition is then mainly attributable to the use of kerosene for lighting which has reduced over time to make way for lighting devices powered by electricity from distributed solar panels or centralised electricity grids. As Uganda's infrastructure develops, households might transition to higher income levels and/or become urbanised, which, given our study, will lead to an increase in CO_2 emissions. An increase in the efficiency of devices alongside the country's growth may help constrain energy use and reduce health and environmental effects of current practices. This will be true for other countries and, since NDC may sometimes be determined by aggregating or averaging devices used at a national level, which will be a particular issue for household groups where improvements may not be identified.

The slow transition for cooking and the differences in stove efficiencies highlight the opportunity to introduce standards or labelling. Such policy instruments can help consumers make informed purchases and increase the average stove efficiencies. This supports a similar call from other studies, e.g. Price (2017).

The transition for lighting, where kerosene use has reduced over time, has been the result of innovation in equipment, business models and promotion of the technology. Cooking is likely to change in the future too with the interventions and programmes underway. Nevertheless, the evaluation of both useful energy and emissions for countries in such transitions can help evaluate the households that require additional efforts. There are more end-uses that can benefit from the approach used in this study, if more comprehensive data were available. Given the higher degree of change in lighting energy sources compared to cooking, other services can be studied to recognise and propose changes in energy provision. Additionally, given the variability in households' conditions and energy use, this chapter and its quantification of useful energy uncertainty demonstrated a method that may be incorporated to national statistics and analysis to increase the confidence on the results drawn.

5

Policies and the resource chain

The aim of this thesis is to provide insights on human well-being and emissions reduction by quantifying service provision. The findings of Chapter 3 showed that the study of the nature of the correlations between service provision and well-being depend on the service studied and insights on which service provision indicators to focus on may be obtained. In particular, final energy resulted a useful indicator to focus on for the services of Transport, the sector of Services Thermal Comfort and Sustenance using a well-known regression model, while device ownership is recommended for the service of Communication if a different regression model is employed. The latter suggested that the dynamics of some aspects of service provision and the dynamics of development have not changed simultaneously. The finding may be of interest to policy makers as they focus on the energy transition or energy access to provide well-being. Chapter 4 then presented how developing country data scarcity can be addressed by using household surveys to inform service provision, particularly energy end-uses. Chapter 4 found that the efforts to change energy provision in Uganda have only had a mild effect on the population's lighting practices, while cooking has remained stubbornly attached to biomass burning, regardless of the expenditure level, while the type of biomass that prevailed depended on the type of settlement. The use of firewood remains prevalent for rural settlements and charcoal for urban ones. Additionally, an increase in emissions was observed as households urbanised and moved to higher expenditure levels.

Policies can be used to regulate the necessary changes in energy provision in developing countries and the need to incentivise the adoption of different practices. Thus, both Chapters 3 and 4 confirmed the need to examine policies surrounding the resource chain since the expected transitions must be regulated and informed by technical research on where to focus efforts.

The aim of this chapter is to characterise the inclusion of resource transformation stages in global energy policies in recent years. Recent energy policy literature shown in Chapter 2 has made advances in the identification of the types of policies and instruments that will favour energy transitions. However, despite this progress, much of the focus of policy research is around primary energy, mainly renewable electricity generation, with few advances in considering other resource transformations and policies that consider systemic change. Policy balances are among the novel ways to research policy mixes that, unfortunately, focus solely on policy instruments used in energy generation policies. Furthermore, even when knowing that climate change is a global problem, policy analysis has mostly covered developed country systems, while fewer studies cover policies for climate-compatible development. Thus, studying how energy policies that consider both contexts of developed and developing countries are changing and regulating service provision, may show if any parts of the chain are disregarded.

Figure 5.1 shows the parts of the resource chain considered in this chapter, along the research question.

RQ3: *Where along the resource chains are energy policies focused both historically and at different country development levels?*

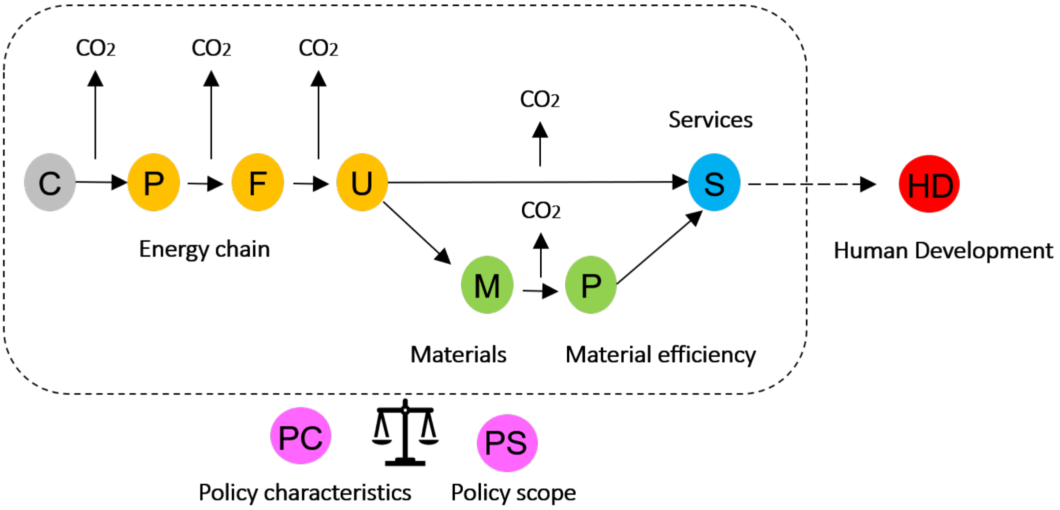


Fig. 5.1 Resource chain to provide services and the parts considered in this chapter. The dashed box shows that this chapter focuses on the characteristics and scope of policies regulating parts of the resource chain.

This chapter is structured as follows: Section 5.1 shows the data gathered to inform this study and the methods used in the analysis. Section 5.2 presents the results obtained and section 5.3 discusses the key findings. Finally, the findings are summarised in section 5.4.

5.1 Data and Methods

The aim of this chapter is to analyse energy policies for countries at different development stages, to determine which parts of the resource chain these policies focus on. To enable this analysis, data is collected from public databases that cover 174 countries at varying development levels.

5.1.1 Policy data

Detailed metadata was compiled for national energy policies implemented between 1960 and 2020 and across 174 countries. The data was sourced from four public policy databases, as shown in table 5.1. The data included the policy scope, location, jurisdiction, scope, and status. The jurisdictions ranged from municipal to international, but with a main focus on national-level policies.

Table 5.1 Policy databases used in the study.

Organisation	*Source*	*Scope*
EUR-LEX	European Union (2020)	European Union laws on energy and industrial policy
CLASP	CLASP (2020*b*)	International energy efficiency database
ODYSSEE-MURE	ODYSSEE-MURE (2020)	European Union policies and measures on energy efficiency
IEA	IEA (2020*c*)	International Policies and Measures

Table 5.2 provides the jurisdictions used to group the energy policies. It shows that national policies dominate, with over 4,500 energy policies in the database.

Table 5.2 Sample size (n) of the policies involved in the study by jurisdictions available.

Jurisdiction	*n*
City/Municipal	98
International	148
National	4,523
State/Provincial	806

Table 5.3 is used to group the policies by status, depending on their implementation stage. The majority, some 9,144, are in force, while over 1,000 had ended by the time the database was collected i.e. 2020.

Table 5.3 Sample size (n) of the policies involved in the study by status.

Policy Status	*n*
Ended	1,157
In force	9,144
Not into force	403
Pending implementation	19
Planned	13
To be updated	2
Under development	140
Under revision	107

Table 5.4 shows the regional classification used to group the energy policies, which are adopted from the MESSAGE model (IIASA, 2013) (any missing countries in the MESSAGE

model region classification are updated, most of which are pacific island nations). The number of energy policies obtained for each region is given by the column n. The best-represented region was the European Union (EU) with 3,042 policies, while the worst-represented was South Asia with only 299 policies.

Table 5.4 Sample size (n) of the policies involved in the study by region according to the MESSAGE model classification

Region	Region Name	n
AFR	Sub-Saharan Africa	363
CPA	Centrally planned Asia and China	558
EEU	Central and Eastern Europe	955
EU[a]	European Union	2,717
FSU	Former Soviet Union	209
GLOB[a]	International coverage	3
LAC	Latin America and the Caribbean	815
MEA	Middle East and North Africa	337
NAM	North America	1,248
PAO	Pacific OECD	559
PAS	Other Pacific Asia	655
SAS	South Asia	299
WEU	Western Europe	3,042

[a] These categories were added to the classification to better represent the data. EU refers to European Union policies and GLOB refers to international organisations operating in several regions.

Figure 5.2 shows the total number of policies per region and their share per year. Most policies available are for Western Europe, especially for the earlier years considered and, more generally, for the European Union.

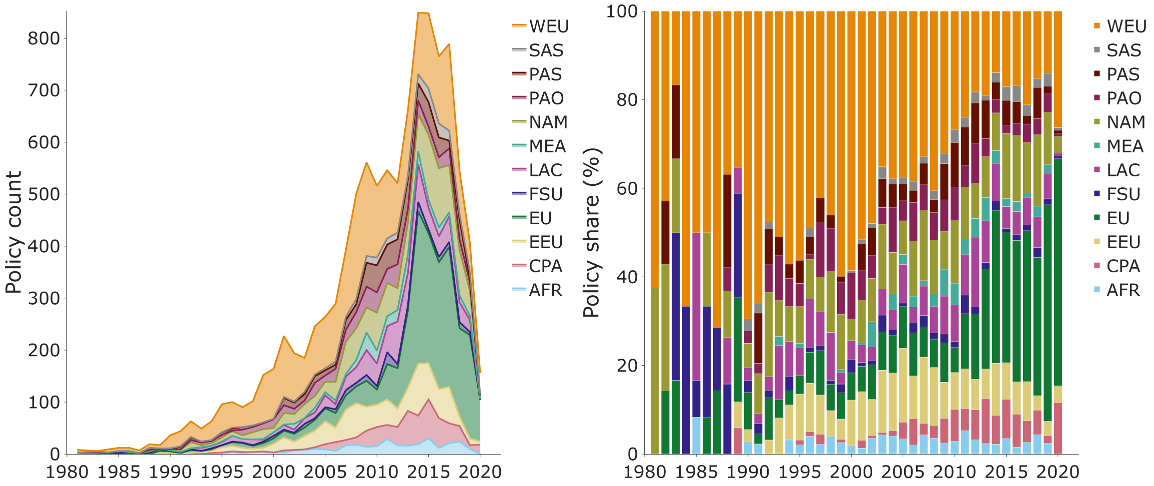


Fig. 5.2 Total number of policies (left) and policy shares (right) per region for n = 10 519. The labels refer to the following regions: AFR: Sub-Saharan Africa, CPA: Centrally planned Asia and China, EEU: Central and Eastern Europe, EU: European Union, FSU: Former Soviet Union, GLOB: International coverage, LAC: Latin America and the Caribbean, MEA: Middle East and North Africa, NAM: North America, PAO: Pacific OECD, PAS: Other Pacific Asia, SAS: South Asia, WEU: Western Europe.

Table 5.5 breaks down the energy policies by country. Canada, the United States of America and China have the most policies in the dataset. In contrast, many Pacific island and Sub-Saharan African nations have only one or two energy policies in place.

Table 5.5 Summary of countries associated with the policies studied

Location	Count
ADB	2
Albania	8
Algeria	16
Angola	15
Antigua and Barbuda	3
Argentina	55
Armenia	8
Australia	278
Austria	132
Azerbaijan	9
Bahrain	3
Bangladesh	14
Barbados	5
Belarus	12
Belgium	151
Belize	4
Bolivia	15
Bosnia and Herzegovina	5
Botswana	7
Brazil	103
Brunei Darussalam	2
Bulgaria	55
Burkina Faso	4
Burundi	6
California	12
Cambodia	1
Canada	693
Chile	60
China	432
Colombia	39
Cook Islands	1
Costa Rica	39
Croatia	54
Cuba	5
Cyprus	68
Czech Republic	78
DR Congo	6
Denmark	87
Djibouti	1
Dominican Republic	4
ECOWAS	8
Ecuador	14
Egypt	21
El Salvador	14
Estonia	67
Ethiopia	12
European Union	2140
Fiji	4
Finland	158
France	246
Gambia	1
Georgia	11
Germany	333
Ghana	24
Greece	109
Guatemala	12
Guyana	10
Honduras	10
Hong Kong	27
Hungary	101
Iceland	6
India	201
Indonesia	86

Location	Count
Iran	67
Iraq	2
Ireland	161
Israel	32
Italy	189
Jamaica	11
Japan	176
Jordan	33
Kazakhstan	10
Kenya	20
Kiribati	4
Kuwait	6
Kyrgyz Republic	3
Laos	6
Latvia	93
Lebanon	7
Lesotho	6
Libya	2
Lithuania	79
Luxembourg	77
Madagascar	4
Malawi	7
Malaysia	26
Maldives	8
Mali	5
Malta	80
Marshall Islands	3
Mauritius	11
Mexico	227
Micronesia, Fed. Sts.	2
Moldova	29
Mongolia	7
Montenegro	3

Location	Count
Morocco	20
Mozambique	5
Myanmar	6
Namibia	14
Nauru	3
Nepal	3
Netherlands	180
New Zealand	97
Nicaragua	22
Nigeria	32
Niue	1
Norway	116
Oman	6
Pakistan	19
Panama	20
Paraguay	11
Peru	26
Philippines	42
Poland	72
Portugal	153
Qatar	5
Romania	68
Russia	67
Rwanda	12
Samoa	9
Saudi Arabia	17
Scotland	8
Senegal	4
Serbia	55
Seychelles	12
Singapore	46
Slovakia	117
Slovenia	70

Location	**Count**
Solomon Islands	5
South Africa	84
South Korea	164
South Sudan	1
Spain	218
Sri Lanka	7
St. Lucia	5
St. Vincent and the Grenadines	2
Suriname	4
Sweden	136
Switzerland	94
Syria	1
Taiwan	134
Tajikistan	14
Tanzania	8
Thailand	74
Tonga	2
Tunisia	22
Turkey	57
Turkmenistan	4
Tuvalu	1
UN	2
Uganda	21
Ukraine	33
United Arab Emirates	24
United Kingdom	189
United States	529
Uruguay	35
Uzbekistan	4
Vanuatu	2
Venezuela	15
Vietnam	72
WAEMU	1
Wales	2
World Bank	2
Yemen	1
Zambia	9
Zimbabwe	8

Table 5.6 shows the categories of interest in each policy and examples of the labels associated to each. The labels in each category have a structure that goes from general to specific aspects, known as classes and labels, e.g. ‘transport end-uses’, ‘freight transport’, and ‘medium trucks’ can all be assigned to a single policy.

Table 5.6 Policy categories of interest for classification

Category	Total unique labels	Examples of labels
Sector	81	Buildings, Generation, Transport, Services, Household, Industry
Technology	202	Appliances, Batteries, Boilers, Cooling fan
Topic	5	Energy efficiency, Renewable energy, Climate change, Methane, Carbon Capture Utilisation and Storage
End-use	34	Building end-uses, Transport end-uses, Electricity end-uses, Existing buildings
Instrument type	115	Regulatory instruments, Economic instruments, Codes and standards, Voluntary approaches

5.1.2 Development data

Four indicators are used to grade the development level of the 174 countries in the study. The indicators were obtained from the World Bank (2020*f*). The indicators are:

1. Life expectancy at birth (LExB) in years. Source: UNDP (2020*b*).
2. Gross National Income per capita with PPP (constant 2011 international $) (GNI) as a rate. Source: UNDP (2020*b*).
3. Average total years of schooling for adult population (AVYSch) in years. Source: UNDP (2020*b*).
4. Gini coefficient (GINI), which, according to World Bank (2020*c*), measures the“extent to which the distribution of income (or, in some cases, consumption expenditure) among individuals or households within an economy deviates from a perfectly equal

distribution." A GINI of 0 represents perfect equality, whereas 100 implies perfect inequality. Source: World Bank (2020*c*).

These four development indicators are similar to those used in Chapter 3 with the addition of the GINI.

5.1.3 Methods

Several methods and tools are used in this chapter to determine the missing characteristics of the policies in the database. Such characteristics are then used to define the stages of the resource chain that each policy refers to, and the stages are paired to the development levels of each country.

First, the policies are split into the categories that define their scope. For any missing categories in the data, a machine learning technique called Natural Language Processing (NLP) is used, which is applied to the policy database, as shown in section 5.1.4. Then, balances of policy categories by sector are quantified as shown in section 5.1.5 to identify differences in the instrument type used and policy scope over time. Then, the policies are classified according to the resource chain as shown in 5.1.6. Finally, the indicators used to compare country changes and development are presented in section 5.1.7.

5.1.4 Natural Language Processing (NLP) for text classification

Natural Language Processing (NLP) is a machine learning application that Liddy (2001) defines as a “theoretically motivated range of computational techniques for analysing and representing naturally occurring texts at one or more levels of linguistic analysis". The origins of NLP can be traced back to machine translation in the 1940’s (Sparck Jones, 2001), although research began in earnest in the 1950’s with the development of an automatic translation from Russian to English. Since then, increasing computation power and developments in linguistics facilitated the creation of improved models. By the 1990’s, new techniques were developed that did not rely on specific linguistic models, but rather on statistical relationships. The field of NLP has since grown further allowing for models to be trained and applied to new problems. This allows for NLP to have a wide range of applications such as categorising or clustering text, modelling topics, extracting information or relationships from text and analysing sentiments.

The NLP application of interest for this study is text classification. The main steps involved are shown in figure 5.3. The process begins by obtaining text from the desired source, some of which may contain some relevant labels, e.g. if Twitter messages that have certain labels (i.e. hashtags) are collected, other messages may be analysed to see if any of those hashtags fit the content as well. The selected text is divided into a dataset with previously identified labels and missing ones. The dataset that contains labels is used to train the model that can be applied on the dataset with missing labels. The dataset that contains labels is first split into test and training sets. The training set is processed in what is known as a *pipeline*, which is a set of transformations that the input needs to undergo. The pipeline may consist of a text cleaner (where blank spaces and other irrelevant and erroneous characters may be removed), a vectoriser (where clean text is broken down into words, phrases, symbols or other significant elements known as tokens which are then converted into a matrix that associates numbers to the tokens, e.g. in the form of a weighted matrix), and a classifier (where defined statistical techniques are applied to the data, depending on the type of classification required). After the pipeline steps are completed and the model works it is applied to the test set to determine how the model performs (e.g. accuracy). Once a model has the desired performance, it can be saved and applied to the dataset with missing labels to predict them.

The classifier step in the pipeline is perhaps one of the most important ones, given the many types of classifiers. The choice of classifier depends on the type of classification required and the desired statistical method. The type of classification can be binary (when the labels are only two possible), multi-label (when more than one label can be assigned to each predictor, e.g. movie genres), multi-class (when different levels of labels need to be assigned, e.g. food types) and a combination of the latter two (where both different labels and classes need to be assigned).

Software to perform NLP is becoming increasingly common, with the programming language python being at the forefront of the work with libraries such as scikit learn (Pedregosa et al., 2011), nltk (Bird et al., 2009), spacy (Honnibal and Montani, 2017) and pickle (Van Rossum, 2020), which contain several language models with applicable characteristics, facilitate the creation of pipelines, and aid in saving and reusing models.

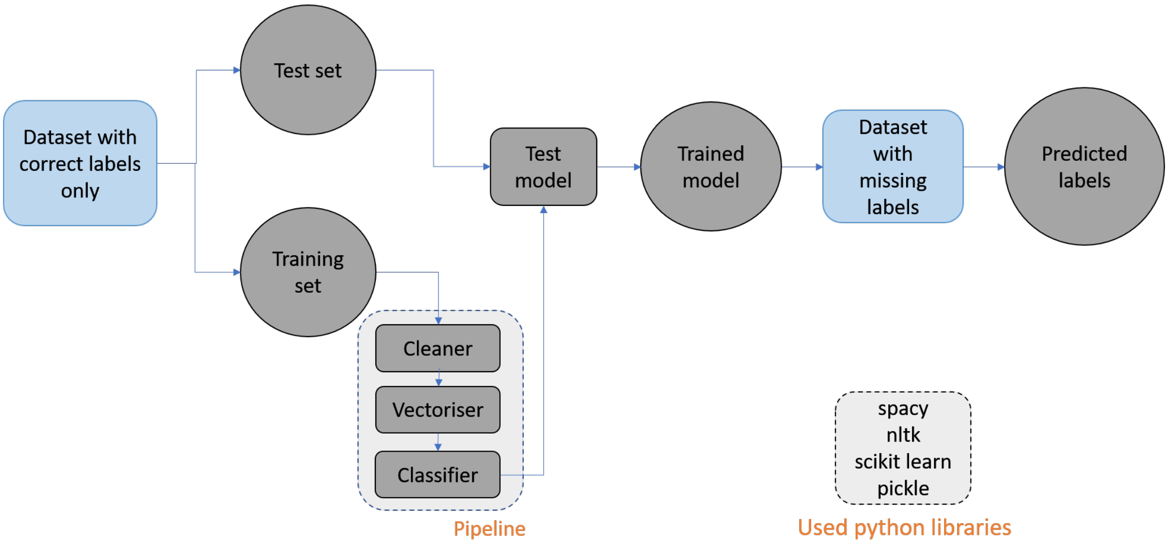


Fig. 5.3 Steps used to create an NLP model for text classification.

Applying NLP in policy classification

The data collected for this study contained different types and levels of information about each policy including the types of instruments used, the year they were implemented, whether they were active or not. The information available varies by policy and data source and NLP can be used to classify missing policy categories. Classifying the policies remediates gaps in the dataset gathered and allows for more accurate conclusions to be drawn about the policies. Furthermore, the ultimate goal of classifying policies according to their resource chain scope is facilitated, as presented in section 5.1.6.

The categories in the policy database that are selected for applying NLP are: sector, technology in scope, policy topic, instrument type and end use. The number of labels in these categories are varied, so a single policy may have several labels associated with a single category with different levels or classes. The type of classification required in this study is multi-class and multi-label, given the characteristics of the labels in each policy category. The algorithm selected to perform the classification is k Nearest Neighbours. The algorithm is explained in the next section.

The K Nearest Neighbours (kNN) algorithm

The kNN algorithm is one of the most commonly used in practical applications of NLP classification due to low calculation times and relative ease of use. Examples of such applications are tailored recommendations to users of streaming services or online shopping. The kNN algorithm determines labels by estimating the distance between the numerical values obtained in the previous stage of the pipeline (vectorisation). If the distance between the points is small, then the points are considered the 'nearest neighbours'. The Euclidean distance (d) is commonly used in this algorithm, which is is the ordinary straight-line distance between two points (p and q) in the Euclidean space, as defined in equation 5.1.

$$d(p,q) = d(p,q) = \sqrt{(q_1 - p_1)^2 + (q_2 - p_2)^2 + ... + (q_n - p_n)^2} = \sqrt{\sum_{i=1}^{n} (q_i - p_i)^2} \quad (5.1)$$

Some shortcomings of the kNN algorithm are that the accuracy of predictions depends on the quality of the data, having low prediction accuracy in points near the established boundaries. An additional consideration when applying this model is the need for finding the best-performing number of neighbours (k).

The NLP classification performed in this Chapter uses a kNN algorithm due to the ease of implementation, low calculation times (since several models will be run for each category) and confidence in the quality of the pre-existing labels of the data gathered. The kNN algorithm is implemented using scikit learn's KNeighbors classifier.

KNN algorithm applied to the policy database

Table 5.7 shows some model specifications for the kNN algorithm in the policy database including the predictor used for each category, the unique labels per policy and the total unique labels. The number of unique labels that the models can choose from vary per category, where the lowest number is for Topic and the highest for Technology. The policy title is used as the predictor because it contains relevant keywords. The predictor of Technology includes the first End-use because of the links between end-uses and technologies, e.g. transport end-uses are linked to cars or trucks, thereby leading the classification in the right direction.

Table 5.7 Summary of NLP model specifications by category.

Category	Predictor (X)	Unique labels per policy[a]	Total unique labels[b]
Sector	Title[c] and End-use[d]	16	81
Technology	Title and End-use	32	202
Topic	Title	4	5
Instrument type	Title	17	115
End-use	Title	18	34

[a] This is the maximum number of unique labels for a single policy contained in the originally classified dataset which are used to train the model.

[b] This is the number of all the unique labels across all the originally classified policies from which the model may choose.

[c] Title given to the policy.

[d] The End-use predictor was the first End-use label predicted by the model adjusted to remove False Positives (FP), which are the labels predicted wrongly.

To split the initial data into training and testing, a test size (s) has to be defined, which refers to the fraction of the dataset to include in the test split. In this study, s is varied in each model from 0.1 to 0.9 to obtain the highest possible accuracy before saving the model and applying it to the whole dataset. The models tested for each category also include varying k to find the number that leads to the highest prediction accuracy.

5.1.5 Category balances as a measure of the policy mix

Policy balances were first proposed by Schmidt and Sewerin (2019), who hypothesised that a policy mix with a more balanced combination of instrument types would be more conducive to inducing socio-technical transitions than an unbalanced combination. Thus, in this study, once the policies are classified using NLP, the policy mix is quantified in the data gathered using balances, which are calculated based on the approach used by Schmidt and Sewerin (2019). Their approach is based on the Gini-Simpson index used in ecology (Hill, 1973; Simpson, 1949), which estimates the concentration of populations across different species. This study extends the approach of Schmidt and Sewerin, applying the balance to different policy categories and not only policy instruments. This is to extend the hypothesis by Schmidt and Sewerin and propose that it is not only a balanced combination of instrument types that would be more conducive to socio-technical transitions, but also a more balanced combination of policy categories (which include policy topics, end-uses covered and technologies regulated) for each sector of the economy.

The calculation of the balance with the modification to include additional policy categories is shown in equation 5.2.

$$1-\lambda = 1-\sum_{category \quad type_{m=1}}^{M} p_m^2 = 1-\frac{\sum_{category \quad type_{m=1}}^{M} (categories_m(categories_m-1))}{\sum categories\,(categories_m-1)} \tag{5.2}$$

Where the term $1-\lambda$ represents the probability that two policies which are randomly picked from a policy mix represent different types of the category in question. M is the maximum number of categories.

The balance is a probability and its value ranges from zero to one, where zero means the policy is unlikely to contain policies with the different category segments and is unbalanced, whereas a value of one refers to a good balance because the likelihood of containing different segments is 100 %.

The sectors considered are: Buildings, Generation, Industry, Services, Household, Transport, General and Multi-sector. The Sector of Agriculture and Fisheries was included in the database, but it is to be removed from the balances due to the low number of policies covered. However it is worth noting that recent policies regulate the efficiency of devices and aim to include the sector in climate change initiatives. An example is the 2011 Dutch policy setting a sectoral emission trading system in horticulture.

5.1.6 Resource chain classification

The policies are divided into categories that contain enough information for a classification of the stage of the resource chain that the policies represent. For the classification, 10,811 unique policies are considered, which may cover more than one technology, and where 4,355 policies contain their original categories and the rest stem from predictions using NLP.

The classification is based on the technologies covered by each policy, where each technology is assigned the corresponding resource chain stages. This means that labels such as ‘primary’, ‘final’, ‘useful’. among others are paired with each technology label, e.g. the label of ‘2 wheelers’ is assigned ‘final’, ‘useful’ and ‘service’, whereas ‘PV Residential’ is assigned ‘source’, ‘primary’, and ‘final’. In case the policies cover more than one technology and their resource transformations are different, e.g. source to primary and final to useful in the same policy, two separate lines are created in the database. This approach is useful during the visualisation of the resource chain covered by the policies studied. Additionally, the classification of the resource chain includes the labels of ‘final 2’ and ‘storage’, which allows electric vehicles and grid storage to be better reflected in the resource transformation. Adding these intermediate stages to the resource chain provides additional granularity to the transformation steps, which improves policy analysis. The classification of all 202 unique technologies are shown in Appendix C.

5.1.7 Global policies and development

The study of resource transformations in policies and the additional data gathered enable comparing the scope of regions and countries. Additionally, and to link this study to Chapter 3, the countries in this database are paired with development indicators to visualise development stages and policy characteristics, depending on the resource chain. The development indicators are paired according to the country and year when the policy was enforced to reflect the living conditions in such year. Regional development values are paired for policies to reflect the region of the EU.

The resulting database obtained after combining policy and development data is extensive and may be used for several analyses. For the purposes of this study, the analyses of interest are the ones shown below.

1. The changes in the resource chain stages included in energy policies over the last two decades.

2. The resource chain stages included in energy policies at changing income and inequality levels.

Interactive visualisation tool

The breadth of research avenues from the resulting database were motivation to create an interactive visualisation tool of the database. Several options have been considered, and the resulting tool is a python interactive widget (a stand-alone application with a user interface). The interactive visualisations contain a top graph showing a scatter plot of years versus a selected development indicator (income, life expectancy, gini coefficient and average years of schooling) and a bottom graph showing the resource chain stages considered by the policies. Two kinds of widgets are developed: one for global policies and one for countries and regions.

The widgets allow for a selection of the policies in the top graph to be made by dragging the cursor around the area of interest. The selection can be used to highlight the policies in the bottom graph. Several selections are possible using different colours to enable comparisons.

Another feature for users is the selection of the desired development indicator from a drop-down menu. As for the widget with countries and regions, it is possible to specify whether only the country or the entire region are to be included in the graph. Additionally, when using the tool, the widget allows for countries to be identified by situating the cursor on specific points in the scatter plot and showing the country labels and specific values. Examples of the widgets will be shown in the sections below with the comparisons of interest for global, country and regional policies.

Limitations of the study

The limitations of the analysis are the following:

- The policy database gathered included many more policies from OECD and EU countries, making it more difficult to apply the insights gained to developing countries. The bias towards developed nations occurs because more policies have been created in the developed nations, and these have been tracked and analysed in more depth by academics.
- The results from the visualisation tool created to show country policies and levels of development can be interpreted quantitatively insofar as general comparisons are carried out. However, a more rigorous statistical analysis is required to make conclusions about the relationship between number of policies in each part of the chain and development levels.
- Policy implementation is more difficult in countries where the rule of law is undermined by political interventions, yet analysing this was outside of the scope in this chapter.

5.2 Results

This section presents the main results, focusing first on the policy classifications, followed by results using such classifications. Section 5.2.1 shows the results from the policy classification using NLP. Section 5.2.2 uses the classified categories and shows the policy balance results. Section 5.2.3 then uses the classified policies to show the result of linking them to parts of the resource chain. Finally, section 5.2.4 shows the tool created to visualise changes in country policies and development levels, along data splits relevant for this thesis.

5.2.1 Policy classification results using NLP

First, the number of neighbours (k) that produced the highest prediction accuracy were obtained. Then, the values were applied in the kNN algorithms of all the policy categories to obtain the predicted classifications.

Table 5.8 shows tests to determine the best-performing value of k, with the values $k = \{3,10\}$. In all categories, higher accuracy is obtained with $k = 10$. The values shown in table 5.8 use test sizes $s \geq 0.3$, which implies that the percentage of data used for training the model is 70% or higher. Additional details about the model including the specific steps used in the pipeline can be found in Appendix C.

Table 5.8 Accuracy after variations of varying k in each model, where k= {3, 10}.

	k = 3		k = 10	
Category	Test size	Accuracy	Test size	Accuracy
Sector	0.2	0.344	0.3	0.398
Technology	0.1	0.231	0.1	0.288
Topic	0.1	0.793	0.1	0.795
Type	0.2	0.290	0.3	0.329
End use	0.3	0.282	0.1	0.330

Table 5.9 shows the results from the classifications of each category using the kNN model with $k = 10$. The highest accuracy obtained is with the lowest number of labels to predict, i.e. the category of Topic. Generally, the prediction accuracy varied according to the number of labels to choose from, where more labels resulted in lower accuracy. The use of different predictors (Title or Title and End-use) improved the prediction accuracy of the categories with a higher number of labels, i.e. Sector and Technology which included the predictors of Title and End-use and resulted in accuracies similar to those of Instrument type and End-use. The category of Technology resulted in the lowest prediction accuracy (29%). This category contained up to 32 unique labels to assign to each policy so, given the possible number of labels, the prediction accuracy obtained is acceptable. The unclassified policies included titles in a different language, so the processing of text in the algorithm automatically removed them, leading to unclassified policies.

Table 5.9 Summary of NLP classification results by category.

Category	Test size [a]	Accuracy (%)	Unique labels[b]	n before NLP	n after NLP	Unclassified[c]
Sector	0.3	39.8	16	6,836	10,804	7
Technology	0.1	28.8	32	4,438	10,804	7
Topic	0.1	79.5	4	5,593	10,804	7
Instrument type	0.3	32.9	17	8,612	10,804	0
End use	0.1	33.0	18	3,086	10,804	7

[a] The test size is the proportion of the dataset to include in the test split to conform the training set.

[b] These are the maximum number of possible labels that each kNN model could assign based on the policy database labels.

[c] These are the policies where no labels were assigned.

5.2.2 Policy balances of each category by sector as a measure of the policy mix

This section shows the policy balances to measure the policy mix for each relevant sector and category of global policies. The balance is a probability, where zero means the policy is unlikely to contain policies with the different category segments and is unbalanced, and a value of one refers to a good balance. The policies included consider the categories classified using NLP.

Figure 5.4 shows that the balances obtained are close to one for most years and sectors apart from the sectors of Services and Household. Thus, the policies analysed tend to be well-balanced for the four categories shown. The Household, Services and General sectors all have low balances for the category of Topic, since most Household and Services policies regulate the Topic of 'Energy Efficiency', whereas the four other Topics are less relevant. The other category in those sectors with low balances in earlier years is the Instrument Type, where the same conclusion cannot be drawn as with Topic, given the typically extensive use of instruments. This means that in those years, only certain Instrument Types would be typically applied to these Sectors, particularly the Services Sector. The sector labelled as General also shows a relative low mix of Technologies, which is unsurprising given how broad the Sector is.

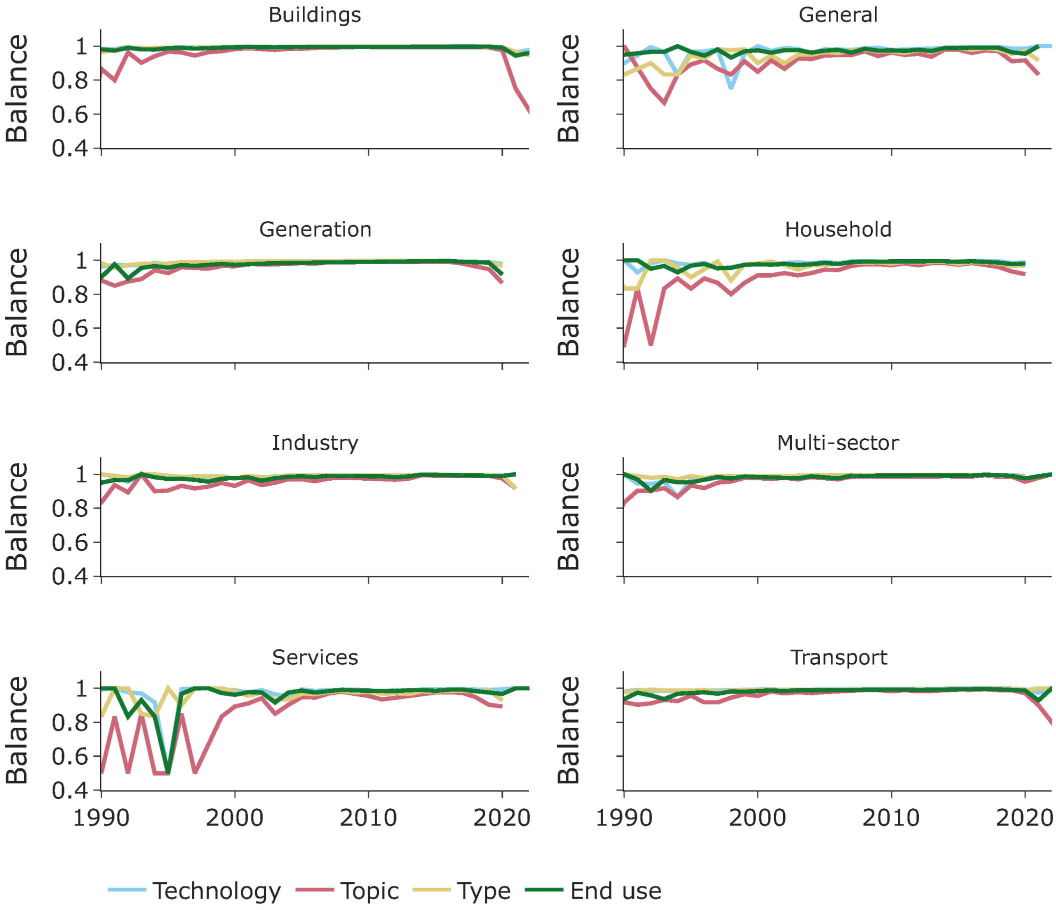


Fig. 5.4 Policy category balances by year and sector (n = 10,811 unique policies). The balances are split by Sectors and are presented for the categories of: Technology, Topic, Instrument Type and End-use. Note the graph titled 'Services' refers to the sector and not the other meaning associated with the resource chain.

5.2.3 Global policies and their resource chain scope

This section explores the stage of the resource chain that the policies in the database cover. The classification was done based on the Technology category of the database and has $n = 10,811$ unique policies that may cover more than one technology. The stages of the resource chain considered are: Source, Primary, Final, Storage, Final 2, Useful and Service.

Figure 5.5 shows the regions (left) and sectors (right) of global energy policies between 1960 and 2020. The lines are coloured by region. The sectors of Buildings and Transport have the highest number of policies, while Europe (as WEU, EU and EEU) and North America

(NAM) have the highest number of policies. Regions that have less policies in the database, such as the Pacific regions (PAO, PAS) or Latin America (LAC) have a high share of policies for Buildings, followed by Generation. Sub-Saharan Africa (AFR) policies are split mostly between Generation and Buildings.

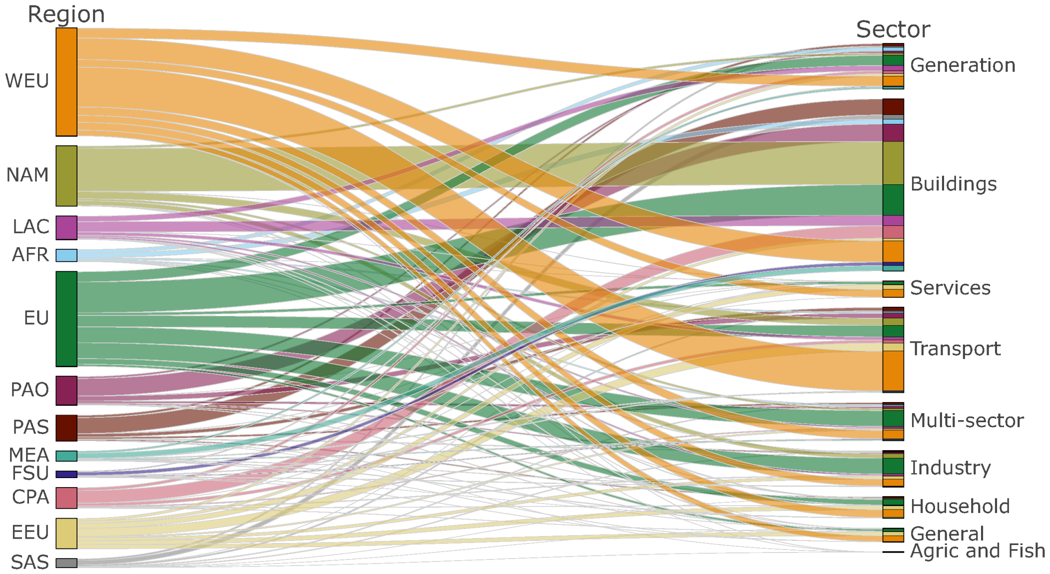


Fig. 5.5 Global policies by region (left) and sector (right) in 1960-2020. The colours refer to the regions. These policies include the ones classified via NLP. The labels refer to the following regions: AFR: Sub-Saharan Africa, CPA: Centrally planned Asia and China, EEU: Central and Eastern Europe, EU: European Union, FSU: Former Soviet Union, GLOB: International coverage, LAC: Latin America and the Caribbean, MEA: Middle East and North Africa, NAM: North America, PAO: Pacific OECD, PAS: Other Pacific Asia, SAS: South Asia, WEU: Western Europe.

Figure 5.6 shows the stages of the resource chain covered by global policies, with the bars coloured by regions. The stages of Useful and Final energy have the highest share of policy coverage in the database. European policies, mainly WEU, have the highest share of Useful, Final and Service stages. WEU also contains the majority of policies related to Storage. NAM and Centrally-planned Asia (CPA) show a higher share of policies in the Useful and Service stages, followed by Final. Developing country regions such as AFR have a higher share of policies around initial stages of the chain, such as Final.

The prevalence of policies in the Buildings sector reflects the focus and complexity of the sector, since regulations include several aspects, which regulate construction practices, operational efficiency, safety and equipment use. Buildings have also included several energy efficiency initiatives and construction employment regulations. Further, policies for Buildings are inherently focused on later stages of the chain, which leads to a high share of Useful, Final and Service stages.

The case of Transport may be the second-most complex, since there is regulation of roads, vehicles, fuels, and users, including the more recent introduction of policies to reduce transport emissions. Transport policies are also associated more to later stages of the chain.

The share of industrial policies can be compared to multi-sector policies, both of which are small. In the case of Industry, this reflects both the standardised practices (in cases such as the EU), and little regulation in emerging economies, even with recent policies to regulate emissions or industrial operations.

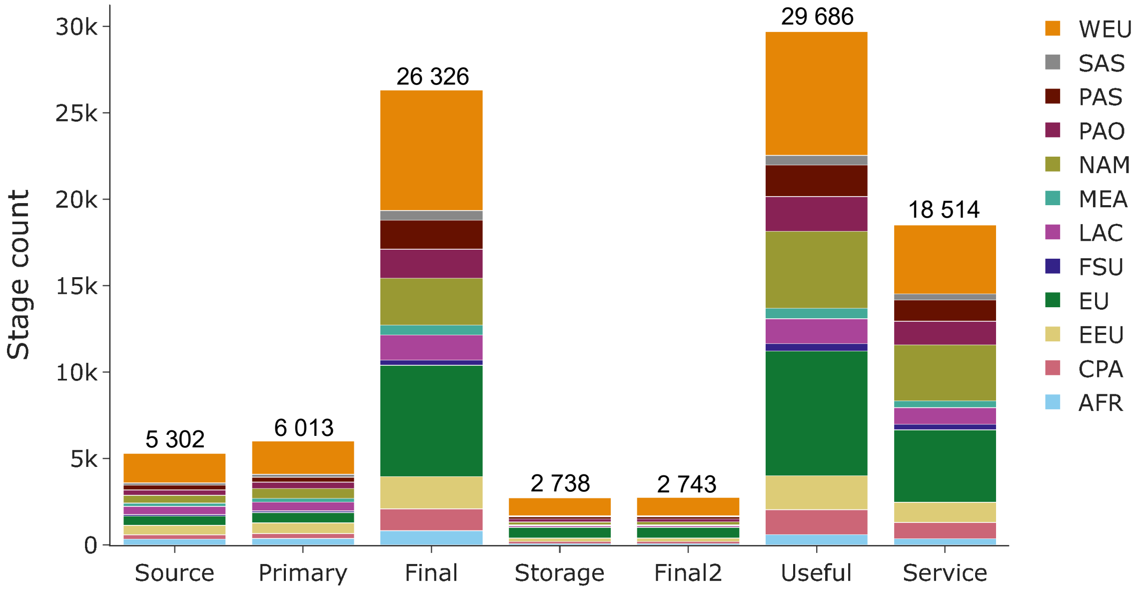


Fig. 5.6 Stages of the resource chain in global policies by region and sector in 1960-2020. The colours refer to the regions. These policies include the ones classified via NLP. The labels refer to the following regions: AFR: Sub-Saharan Africa, CPA: Centrally planned Asia and China, EEU: Central and Eastern Europe, EU: European Union, FSU: Former Soviet Union, GLOB: International coverage, LAC: Latin America and the Caribbean, MEA: Middle East and North Africa, NAM: North America, PAO: Pacific OECD, PAS: Other Pacific Asia, SAS: South Asia, WEU: Western Europe.

5.2.4 Global policies, their resource chain scope and development levels

The following results show the two comparisons of interest using the interactive visualisation tool. The comparisons are: the resource chain stages considered in energy policies between 2000 and 2019, and the resource chain stages in energy policies at varying levels of income. These will be shown comparing global policies, regions and, in some cases, specific countries.

Resource chain in scope for policies in the decades of 2000-2019

Figure 5.7 shows all energy policies implemented from 1960-2019, organised by the country development levels when the policy was implemented. The policies for the decades of

2000-2019 are highlighted using the interactive visualisation tool. The top chart in Figure 5.7 plots all energy policies analysed, with life expectancy (LExB) against time, while the bottom charts show the stages of the resource chain covered by the policies (left) and the regions and sectors involved (right). The two decades are important for global energy policy because international accords have been launched and have come into effect. In the first decade, the Millennium Development Goals (in 2000) (UN, 2000), Kyto Protocol (in 2005) and the EU Emission Trading Scheme (EUETS) (in 2005) (EU, 2005) were established. The second decade saw the establishment of the Sustainable Development Goals (SDG, in 2015) (UN, 2016) and the Paris Agreement (in 2016) (UNFCCC, 2016).

Figure 5.7 shows the increasing trend of LExB in the decades considered. As for the resource chain scope, the policies in the first decade (2000-2009) indicate a focus on the sectors of Buildings, followed by almost equal proportions of Generation and Transport policies, while most of the other sectors are represented in much smaller, yet similar proportions. In the regions considered in this first decade, the policies are implemented mostly in the region of WEU, with smaller contributions form NAM, EEU and PAO. The policies in the second decade (2010-2019) generally have the highest number of policies in the database, given the recent focus on tracking energy policies. The policies show a higher regulation of Buildings, followed by Transport, Industry and Generation. It is during this last decade that policies covering Storage, for both renewable energy generation and transport, have been created. The majority of policies in the last decade are found in the EU and NAM regions. This reflects the international efforts to promote the energy transition and development, as well as recent efforts to shape energy policies in regions outside of Europe and North America. Most policies in the regions of LAC and CPA were added during this decade.

Energy policies have shifted in focus towards the later stages of the resource chain, over the last decade (2010-2019). This is driven largely by an upsurge of Buildings and Transport policies, which are applied at the end of the resource chain, reflecting the fact that such sectors require more regulation towards the end of the chain (with equipment/device regulations). The number of energy policies in the front-end stages of the resource chain (i.e. Source, Primary energy) are equally balanced across the two decades, indicating a consistent effort over time to promote access to electricity and renewable energy generation.

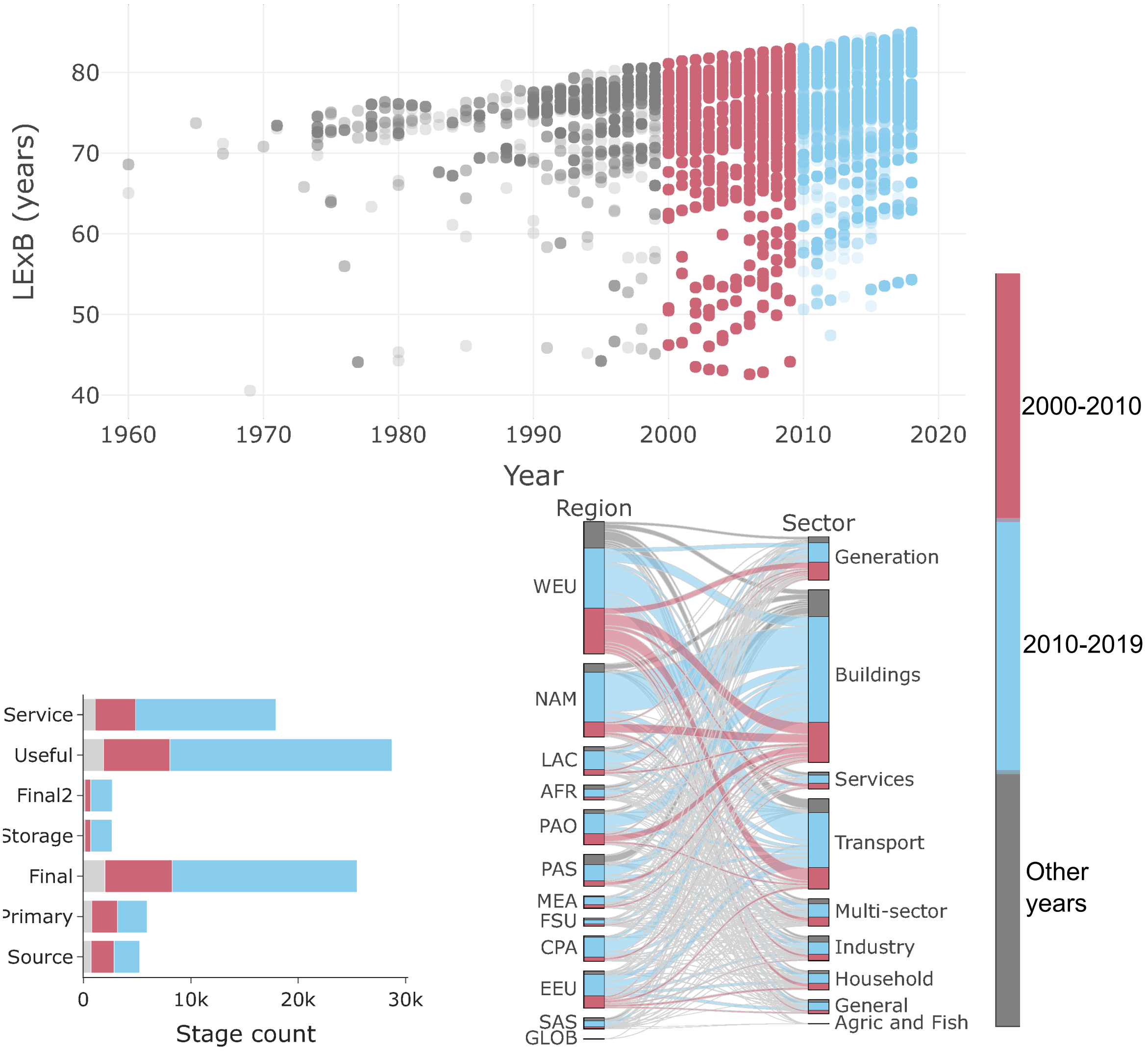


Fig. 5.7 Global policies with life expectancy at birth (LExB) (above), stages of the resource chain (below, left), and regions and sectors (below, right) in 2010-2020. The decades are represented by the following colours: pink for 2000-2009 and blue for 2010-2019. The regions refer to the following: AFR: Sub-Saharan Africa, CPA: Centrally planned Asia and China, EEU: Central and Eastern Europe, EU: European Union, FSU: Former Soviet Union, GLOB: International coverage, LAC: Latin America and the Caribbean, MEA: Middle East and North Africa, NAM: North America, PAO: Pacific OECD, PAS: Other Pacific Asia, SAS: South Asia, WEU: Western Europe.

Resource chain in scope for policies, income and income inequality

Figure 5.8 compares the energy policies studied, over time, against gross national income (GNI) levels. The top chart plots all energy policies analysed, with GNI against time, while the bottom charts show the stages of the resource chain covered by the policies in such income levels (left) and the regions and sectors involved (right). An additional category is included in the bottom right figure referring to income groups based on the World Bank (2020*e*). The data selected in the chart at the top of figure 5.8 uses the same three ranges of income across all years (as defined in the bar to the right), divided by income categories defined in the final year. This prevents countries from moving between income categories, simplifying the analysis, but ignores the changes in income levels with time for individual countries.

The policy database is dominated by High-Income countries (HIC) which is unsurprising given the high representation of EU countries in the database. Policies from Upper Middle-Income countries (UMC) and Low-Income countries (LIC) countries are less represented. However, even with this bias in the database, the figure points to clear differences in the application of energy policies across different country income levels.

- Energy policies in the Low Income Countries (LIC) (in pink) focus on electricity generation sector (left column of the bottom graph), and across the Source, Primary, Final and Storage stages. Storage is a key element of many off-grid solar electricity installations. Energy policies have yet to be developed at any level in the latter end-use and service stages of the resource chain.

- In the Upper Middle (UMC) countries (in yellow), there is evidence of energy policy being applied in services, connected to the development of energy policies for the Buildings and Transport sectors.

- High-income Countries (HIC) (in blue) show a regulation of all sectors and have the highest share of policies that regulate storage for the electricity grid and electric vehicle applications.

The regulation of end-uses and services requires more policies to be created, given the different system configurations used to deliver services, but it also allows for interventions closer to well-being outcomes to be made.

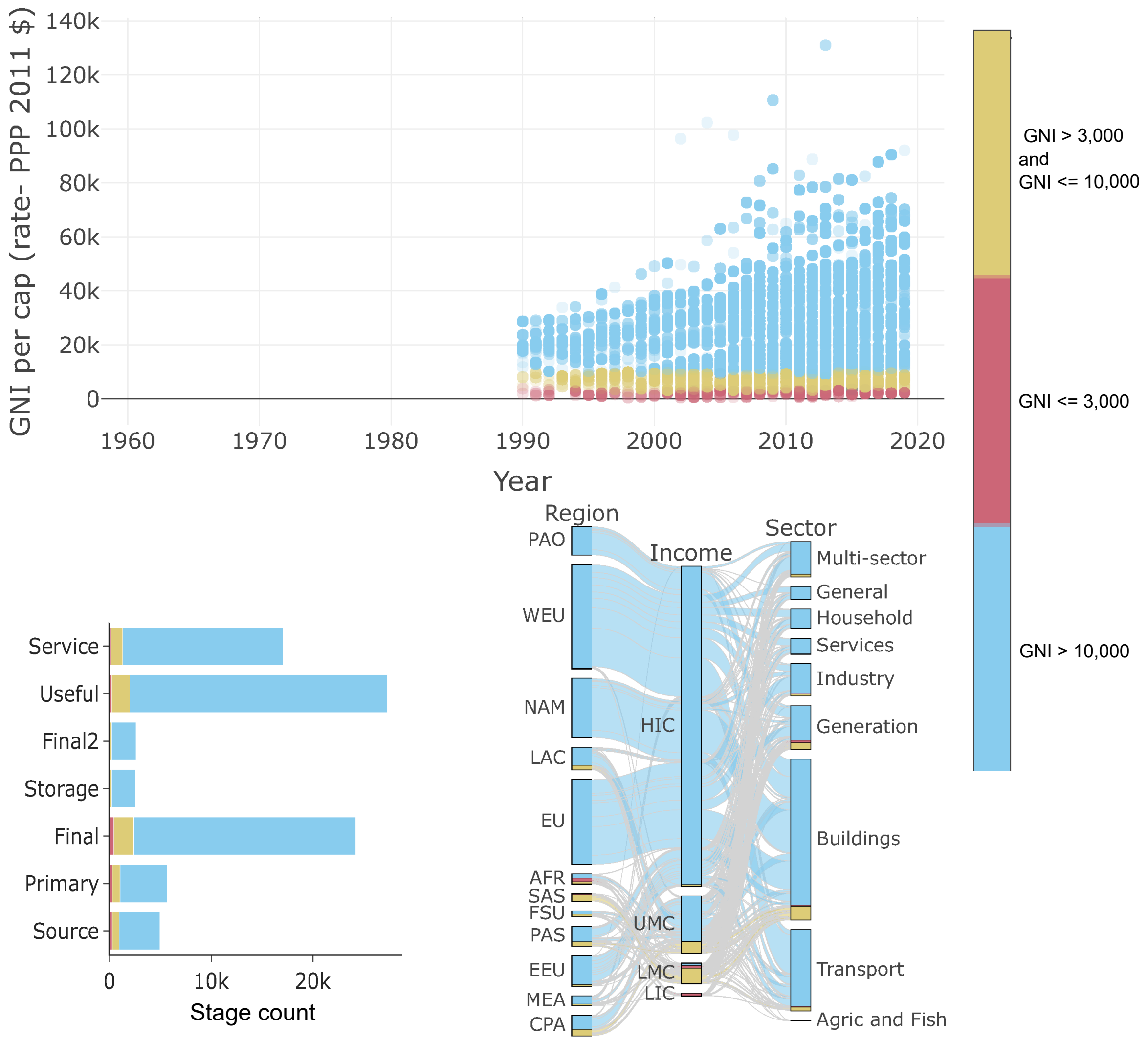


Fig. 5.8 Global policies' income (GNI) levels (above), stages of the resource chain (below, left), and regions, income groups and sectors (below, right) in 1990-2020. Income variations are represented by the following colours: blue for $GNI > 10\,000$, yellow for $10\,000 \geq GNI > 3\,000$ and pink for $GNI \leq 3\,000$. The following abbreviations are used for income groups: High income: HIC, Upper middle income: UMC, Lower middle income: LMC, Low income: LIC. The regions refer to the following: AFR: Sub-Saharan Africa, CPA: Centrally planned Asia and China, EEU: Central and Eastern Europe, EU: European Union, FSU: Former Soviet Union, GLOB: International coverage, LAC: Latin America and the Caribbean, MEA: Middle East and North Africa, NAM: North America, PAO: Pacific OECD, PAS: Other Pacific Asia, SAS: South Asia, WEU: Western Europe.

Resource chain in scope for policies in the decades of 2000-2019 with examples of a country and a region

This section presents examples of the widgets for countries and regions, specifically the UK and Sub-Saharan Africa, in the decades of 2000-2019.

Figure 5.9 shows UK energy policies implemented from 1960-2019, organised by the country development levels when the policy was implemented. The policies for the decades of 2000-2019 are highlighted using the interactive visualisation tool. The top chart in Figure 5.9 plots all energy policies analysed, with life expectancy (LExB) against time, while the bottom charts show the stages of the resource chain covered by the policies (left) and the sectors involved (right).

UK policies have been focused on Transport and the stages of Final and Useful energy in the most recent decade (2010-2019). The policies include renewable energy and electric vehicles, as evidenced by the high share of the stages of Final 2 and Storage. The previous decade (2000-2009) showed a similar share of Buildings and Transport policies. Industrial and Multi-sector policies have a higher focus in 2000-2009.

Figure 5.10 shows Sub-Saharan African policies implemented from 1960-2019, organised by the country development levels when the policy was implemented. The policies for the decades of 2000-2019 are highlighted using the interactive visualisation tool. The top chart in Figure 5.9 plots all energy policies analysed, with life expectancy (LExB) against time, while the bottom charts show the stages of the resource chain covered by the policies (left) and the regions, income categories and sectors involved (right).

Sub-Saharan Africa policies show that in the most recent decade (2010-2019) there has been a focus on Buildings and Generation policies, and the beginning of Transport regulations. The previous decade (2000-2009) shows that policies focused mainly on Generation, with a small fraction focusing on Multi-sector policies and Buildings. This has led to a higher share of policies covering the Final stage of the resource chain in 2010-2019, with a higher inclusion of later stages of the chain, while in 2000-2009 the focus was on the initial stages of the chain. Additionally, industrial policies are being created in the region in the last decade.

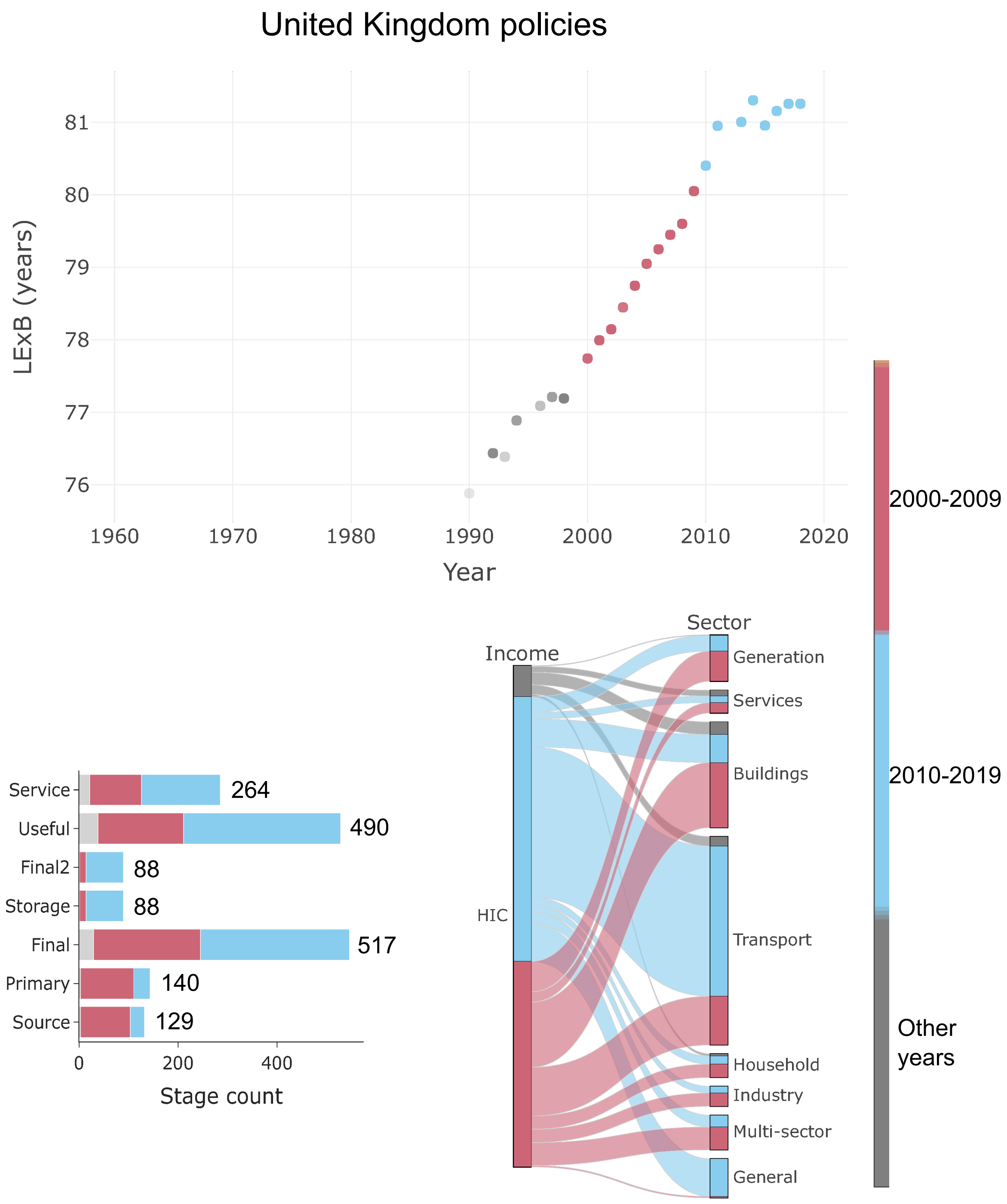


Fig. 5.9 UK policies and their inclusion of resource chain stages focusing on the decades 2000-2019. Life expectancy at birth (LExB) (above), stages of the resource chain (below, left), and sectors (below, right).

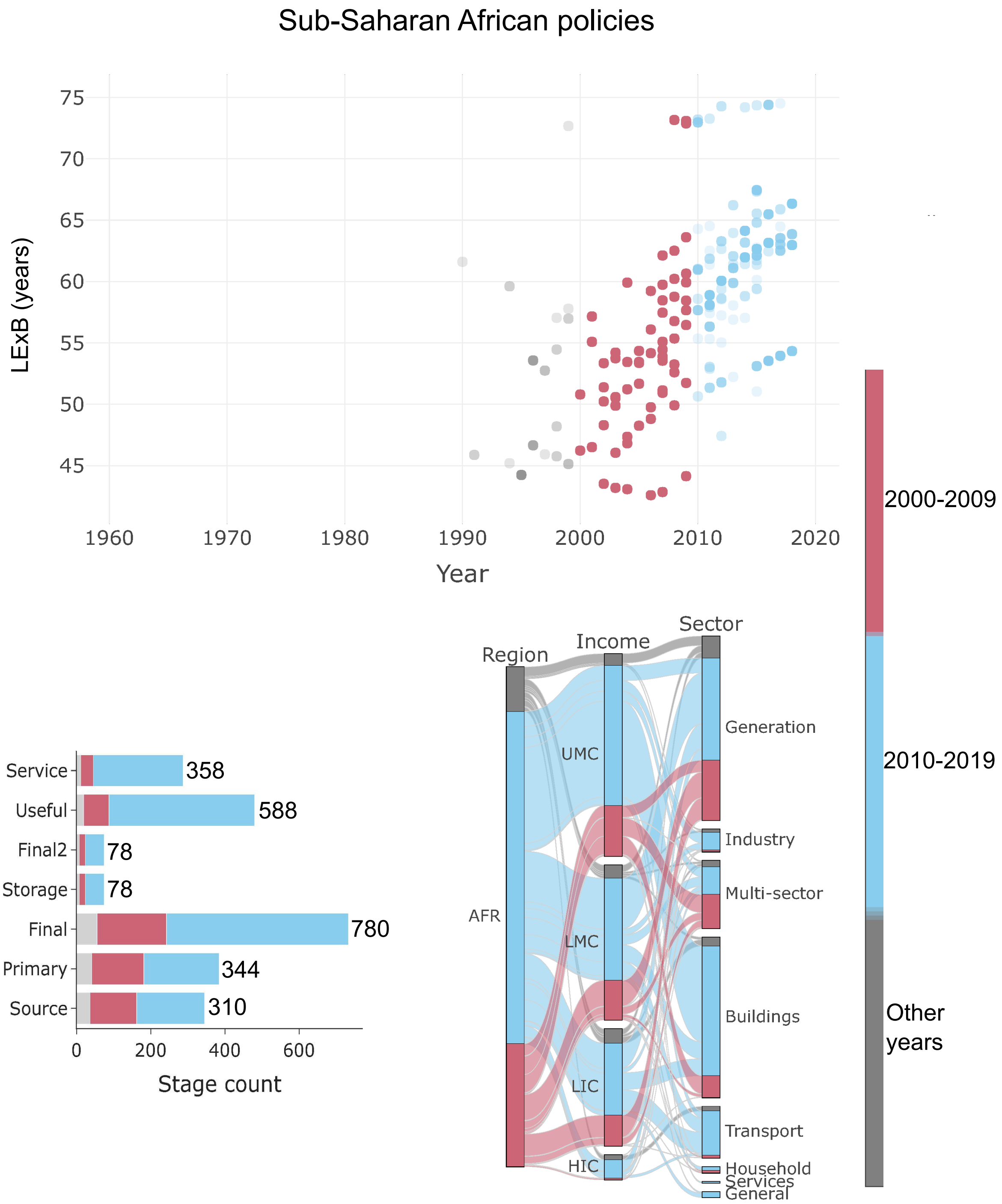


Fig. 5.10 Sub-Saharan African (AFR) policies and their inclusion of the resource chain focusing on the decades 2000-2019. Life expectancy at birth (LExB) (above), stages of the resource chain (below, left), and regions, income categories and sectors (below, right). The following abbreviations are used for income groups: High income: HIC, Upper middle income: UMC, Lower middle income: LMC, Low income: LIC.

5.3 Discussion

This chapter gathered and analysed 10,811 global energy policies to determine, for the first time, which stages of the resource chain they cover. To classify the stages of the resource chain, missing policy categories were first classified using kNN, a NLP algorithm. The categories were: sector, topic, end-uses, technologies and instrument types. The resulting policy database was used to evaluate policy mix balances in each sector, and to determine how the stages of the resource chain have changed over time and according to country income levels.

The policies with missing labels in the categories of interest were classified using a machine learning technique called NLP with a kNN algorithm. The label predictors of each category model were the policy title and, in cases where the number of unique possible labels was high, the first end-use label. The models obtained prediction accuracies varying from 29-80%, obtaining a higher accuracy when the model had lower numbers of unique labels to choose from. The classifications with end-use as predictor achieved an accuracy similar to those with half the number of unique labels to choose from. The lowest prediction accuracy was for the category of Technology, where up to 202 unique labels, with maximum 32 for a single policy, were possible. Despite the challenge for the classification, because the labels contain classes, the resulting prediction tended to be steered towards the correct general area. This proved the usefulness of the kNN algorithm for categorising policies using Title as predictor. In the literature, the prediction accuracy for big data considered acceptable is 60% or above (Deng et al., 2016). This indicates that predictions with lower accuracies in this chapter require further refining of the algorithm. However, the kNN algorithm used for policy classification is still useful for the designed purpose.

The classified database was used to estimate the policy balances by sector and year to determine whether the policy mix balances have changed over time. The policy mixes of each sector resulted well-balanced for most years and sectors, except for the Services and Household sectors. The focus of the Services and Household sectors on energy efficiency, was identified to induce low balances in the category of Topic. The focus of energy efficiency policies, as discussed by the IEA (2020*b*) is to create policy packages to steer demand for efficient products, integrate components such as regulation, incentives and information, while R&D is steered towards enhancing performance. Given the hypothesis by Schmidt and Sewerin (2019) that a policy mix with a more balanced combination of instrument types would be more conducive to inducing socio-technical transitions, the low balances of the sectors of Services and Household indicate that energy efficiency policies and the instruments typically used might not be sufficient for the required socio-technical transition.

5.3.1 Policies for the energy transition and climate-compatible development

The policies for high-income developed countries showed efforts towards regulating energy efficiency, as evidenced by the high share of Buildings policies; efforts towards regulating the energy transition closer to an end-use perspective, as evidenced by the number of policies on Generation; and efforts towards shifting Transport, as evidenced by Transport policies that are also including Storage i.e. electrification of transport. The high number of policies for the Buildings sector and the inclusion of stages from Final to Services show the complexity to regulate services, given the varied configurations for service delivery, where device efficiency, building performance, safety concerns, and even employment play an important role. However, the Buildings sector requires setting up additional measures, such as those recommended by the IRENA et al. (2018, Chapter 1) to take up renewable energy supply integration for the heating and cooling sectors. The changes will require updating the policy packages and integrating options for decarbonisation, beyond the EU, where most of these policies are in place.

The complexity of the Buildings and Transport sectors hides shortcomings in achieving systemic change. There is a setback on energy efficiency policies, as identified by the slowdown of efficiency gains in the services and residential sectors with the relaxation of energy efficiency policies (IEA, 2020*b*), as well as the low investments in efficient buildings related to the COVID-19 pandemic (IEA, 2020*a*). This is also evidenced by lower number of policies for the Buildings sector in the most recent decade (2010-2019) for the UK. Since efficiency policies are known to have brought energy savings in appliances and space heating in the EU (Bosseboeuf, 2015), they should serve as encouragement for uptake in other regions.

Efficiency for freight transport for trucks has slowed down since 2007 in the EU (Bosseboeuf, 2015). The findings of this Chapter suggest that Transport policies have been taken up again in the last decade. Combining this observation with the previous finding of how energy efficiency policies are not enough for socio-technical transitions, updated policy packages for sectors that have been overlooked by the challenges of decarbonising primary energy is required.

The shift of energy-intensive sectors away from developed countries, including EU ones (IEA, 2020*b*), and the fact that industrial policies outside of developed countries have been created only in the last decade (as evidenced by Sub-Saharan African policies), highlights the need to increase industrial policy action in developing or emerging countries. This can have a direct effect on the Paris Agreement goals that many nations ascribed to.

In countries at the lowest income levels, the results showed a prevalence for policies at the primary energy stage between 2000 and 2009, with more policies for resource chain stages closer to services being created only in the last decade (2010-2019). Emerging economies showed coverage of Buildings and Transport policies, but still little coverage of Services. Among them, there are policies for solar water heating or biogas for heating (IRENA et al., 2018). These types of policies have addressed the local contexts and the resources available. These findings offer hope for change. However, the efforts are not enough as shown by the observation from the IEA (2019*a*) regarding the insufficient African Union goals to achieve electricity access and clean cooking for all its population.

Developing countries are shown to be focused on primary energy (Generation) and more recently on Buildings, with some policies including the stage of Storage in the resource chain, which is linked to off-grid solar policies. However, the low number of policies indicates that there are more opportunities to scale up efforts, e.g. increasing the quality and efficiency of off-grid products, which the IRENA et al. (2018) identify to be in place in some developing countries.

This study demonstrates that the regulation of end-uses and services requires detailed policies to be created, given the different system configurations used to deliver services, but it also allows for interventions closer to well-being outcomes to be made. Thus, the findings call for policy making from a more systematic perspective beyond increasing generation and integrating renewable sources, as the World Bank and ESMAP (2018) or Wilson et al. (2012) have also pointed out.

5.3.2 Key takeaways from the policy and development analysis

The policy mix is better-balanced after 2005, showing higher regulation of stages of the resource chain closer to services and increasing complexity due to the interacting policies. Policies for the sectors of Household, Services and some General ones were not well-balanced, especially before 2005. This shows policy making is increasing its scope and use of instruments to achieve their goals. Combining this with the finding regarding policy focus over the past two decades, where the last decade has seen an overwhelming number of policies focused on Buildings, it may be concluded that if the complexity of a sector is high, the policy mix used is also high.

Low-income countries have mainly focused on primary energy between 2000 and 2009, with a recent move towards including final energy policies and beyond for Buildings. The scope of the resource chain in the policies studied showed that low-income countries tended to be focused on energy generation between 2000 and 2009, with an increase of Buildings and some Transport policies between 2010 and 2019, especially in Sub-Saharan Africa. As income levels increase, a broader regulatory scope is introduced. Given the challenge to increase climate-compatible development, low-income countries should not need to wait until some practices or industries are widely adopted for policies to be implemented. This occurred in the off-grid solar industry (IRENA et al., 2018). An example of success in regulating the early adoption of devices is India, whose ‘Affordable LEDs for All’ programme, used bulk procurement to offer LED bulbs at low prices leading to 350 million LED lamps being sold since 2015 (IEA, 2020*b*). Other industries need regulation, especially since they service developed countries.

High-income countries focus on renewable primary energy, Buildings and Transport policies in stages of the chain towards final energy and services. Energy efficiency policies that include the Services and Residential sectors require stepping up actions to not lose momentum from previous years. These policies need to include new ways of providing certain services, such as heating and cooling. The uptake of Transport policies in developed countries has included electrification, leading to a new stage of the chain related to Storage to be defined.

Overall, policies are not concentrated in supply-side technologies, but are spread across the resource chain. With the caveat that regulation further down the chain, in the demand side, requires many more policies, because of the diversity of technologies.

The required socio-technical transition needs many types of policies, including energy efficiency policies in different sectors, the regulation beyond primary energy in developing countries and the regulation of industry in emerging and developing countries. This was evidenced by the low policy mix balances of the sectors of Services and Household, the decreasing impact in energy efficiency and the few industrial regulations outside of developed countries.

The methods and results presented in this chapter will be of interest to policy makers and academics working on energy policy since they enable the study of resource transformations in a systematic way which can be used to complement existing studies. If the resource chain scope of policies is combined with energy use scenarios that predict efficiency improvements or technology uptake, the policy landscape becomes clearer.

5.4 Summary of findings

Chapter 5 investigated which parts of the resource chain are included in global energy policies to describe how energy systems changes are regulated for energy transitions and where policy efforts in international development lag behind. In total, 10,811 unique policies were studied. Of those, between 3,086 and 8,612 contained labels of each of the desired policy categories: topic, end-uses, technologies and instrument types. The remaining policies were classified using a machine learning technique called NLP with a kNN algorithm that demonstrated to be capable of assigning the necessary labels with prediction accuracy varying from 29-80% depending on the maximum number of unique labels to assign. The kNN algorithm proved useful for policy classification. Policy mixes were evaluated for different sectors of the economy through the calculation of balances of the predicted categories. The results suggested that the policies are well-balanced for most sectors after 2005, whereas the policies before then were unbalanced in the sectors of Households, Services, as well as General policies. This indicates that energy efficiency policies and the instruments typically used are not sufficient for the required socio-technical transition. The inclusion of the resource chain in the policy database showed that the focus of policies has shifted in the past two decades going from a focus on the sectors of Buildings, Transport and Generation to an overwhelming number of policies being focused on the Buildings sector followed by Transport. This reflects a shift to regulating activities closer to services in Buildings, and results in a higher complexity reflected by more policies. In countries at the lowest income levels, the results showed a prevalence for policies at the primary energy stage, with growing number of policies and sectors as income grows. Sub-Saharan Africa showed than in between 2010 and 2019 more policies at the later stages of the chain have been created, shifting the focus on primary energy in the previous decade. Developing countries are shown to not achieve climate-compatible development unless detailed policies in both industry and later stages of the chain are included in the policy mix. The required socio-technical transition in developed and developing countries needs many types of policies, including energy efficiency policies, the regulation beyond primary energy in developing countries and the regulation of industry in emerging and developing countries.

6

Conclusions

This thesis has set out to answer the question *‘What insights about human well-being and emissions reduction can be gained by exploring and quantifying service provision?’*. This Chapter addresses the extent to which this question has been answered. Section 6.1 summarises the main contributions to knowledge of this thesis based on the answers to the main research questions. Section 6.2 discusses the wider implications of the work. Finally, section 6.3 elaborates which potential avenues for future work there are that could extend the work or address some of its limitations.

6.1 Specific contributions to knowledge

The main research question in this thesis has been broken down into three questions that have been the basis for Chapters 3-5. Chapters 3 and 4 have focused on gathering evidence on measuring resource transformations that lead to services and linking them to well-being in countries at different development stages. Chapter 5 then looked at recent energy policies to show how parts of the resource chain are included to further inform the links studied in the previous chapters. This section will explore the contributions to knowledge gathered after answering the research questions in each chapter.

RQ 1: To what extent have increases in services delivered been associated with higher levels of development?

To answer the research question, services need to be defined and quantified. However, the quantification of services was in itself a challenge since services are what is achieved at the end of the resource chain and are typically not measured in energy units, e.g. passenger-kilometres for road transport or lumen per square meter for illumination. Chapter 2 showed that studying global services is limited by the availability of detailed data and any link to development has only been studied using aggregate energy quantities, which are far from services.

A systematic identification of the main stages of the resource chain, and an identification of key development indicators used in the literature were used to explore this knowledge gap. Five possible types of service provision indicators were identified and evaluated across, on average, 100 countries. The service provision indicators were gathered for seven services, and covered final energy, device ownership, built stock, social or environmental outcomes, services (indicators with no energy units). Total emissions and total primary energy were also included in the regressions to make comparisons. The development indicators were analysed at two levels: as compound indicators (HDI and IHDI) and their conforming parts (life expectancy, schooling and income). An extensive database was compiled of service provision and development indicators indicators covering 34 indicators, up to 57 years of data and around 80,000 points.

The service provision indicators were used to determine the nature of their correlations with development indicators. The regressions between the selected service and development indicators used a well-known semi-logarithmic functional form. Generally, the regression curves showed that for constant service-related levels, development is decoupling from the service indicators with significant regression results. The regression results were found to change based on five aspects: the service studied, the functional form of the curve fitted, the service provision and development indicators in question, the countries considered and specific temporal dynamics. These aspects interacted with each other.

The correlations between each pair of indicators changed depending on the service studied, since service provision indicators for a single service could show similar results. The correlations with indicators for the service of Sustenance resulted in overall less and lower fits. This was because the semi-logarithmic model did not fit the data or led to non-significant results. In turn, the service of Transport produced more significant results with its service provision indicators.

The curve fitted using the semi-logarithmic model showed that it was valid to study the correlations of particular indicators. The model fitted the following indicators best: road vehicle ownership, fixed telephone subscriptions, total emissions, and primary energy, explaining 81, 78, 69 and 68% of the variance of HDI in 2014 respectively. The variance explained by the first two indicators is higher than what primary energy or total emissions can explain, showing the advantage of considering services and parts of the resource chain. In contrast, some indicators required studying the correlations with a different functional form. In the case of device ownership for the service of Communication, the regressions showed that the incumbent technology of fixed telephones could be studied with the semi-logarithmic model, but over time the model fitted the data less, going from explaining 85% of the variance of HDI in 2005 to only 76% in 2015. Instead, the model did not fit the successor technology of mobile phones at any point in time.

The regressions showed that indicators related to a specific part of the resource chain, which produced significant results, could be identified for different services. The use of final energy indicators for the services of Transport, and the sector of Services Thermal Comfort was shown to produce significant results with the semi-logarithmic model. Thus, the study of such services from a final energy perspective is encouraged. Note that this is beyond final energy for household electricity, since transport is included. Additionally, device ownership for Transport and for Communication could also be studied, including a different functional form for mobile phones. Additionally, obtaining significant results using compound development indicators depended on having significant regressions against their components. If more components were significant and fitted the model well, the model for the compound indicator also performs well. This was observed in the correlations against fixed telephone subscriptions, where the high fit with HDI could be traced mainly to a high fit with life expectancy, while a high fit in road vehicle ownership with HDI could be traced to medium fits (i.e. around 60%) against each component. Further, the inclusion of components can show additional insights on how the regressions are changing over time. This was shown by the regressions with total emissions, where total emissions resulted to be decoupling from compound development indicators, which was due to decoupling from schooling indicators, but the coupling with income was increasing.

The countries considered in each indicator affected the regression results considerably. When service provision indicators included countries near or at the bottom of the development scale, e.g. Morocco in the service of Thermal Comfort, the curve was steeper and covered more variance.

The temporal dynamics that affected the correlations are: (i) the speed of technological change as shown with the service of Communication, (ii) the decoupling with some service provision indicators with development levels, where increases in service provision indicators does not bring further increases in development levels, e.g. life expectancy and total emissions, and (iii) the dynamics of the correlations of the same indicators over time, where a correlation at one point in time does not mean it will remain the same at other times, e.g. the changes in the correlation of total emissions and income over time.

To summarise, for constant service indicator levels, development is decoupling from those service indicators with significant regression results. However, there are dynamics that affect the pace of change of service provision. Therefore, systematic understanding of those dynamics is needed. Further, the identification of service provision indicators highlighted the need to increase data availability in some indicators, especially for developing countries.

RQ 2:What insights on local service delivery may be drawn from harnessing available developing country data?

Many countries are altering parts of their resource chain to deliver services, either by changing existing infrastructure and devices to lower-carbon ones, or by expanding the infrastructure, device availability and energy flows. These changes need to occur while adhering to international low-carbon commitments, i.e. NDC. Evaluating progress regarding the commitments and making changes in service provision require detailed information on energy use and device characteristics.

Chapter 4 set out to identify what insights could be obtained from data gathered at a national level regarding resource transformations, service provision and their environmental impact. Uganda was selected as case-study, using a mixed-methods approach. The methods included a qualitative and a quantitative part. The qualitative part illustrated the local context by conducting seven semi-structured interviews with stakeholders in academia, government, local companies and institutions. The quantitative part included a bottom-up study of household end-uses. National household surveys from 2009 to 2016 were used, aggregating them into settlement type and expenditure deciles. Total final energy, emissions and final to useful energy for cooking were calculated. Useful energy for cooking required a detailed methodology to estimate stove efficiencies and their uncertainty.

The results showed that transitions away from traditional energy sources such as kerosene for lighting and biomass for cooking occurring slowly. Lighting showed a faster transition than cooking, which remains reliant on charcoal. Fuel stacking was common in Uganda, especially in wealthier households, which is slowing the transition away from traditional energy sources, and exacerbating emission increases with urbanisation. Other factors that contribute to fuel stacking and the slow transition are the availability of energy sources and devices, income and local practices. These factors also contributed to slums having lower cooking stove efficiencies than rural households in low expenditure deciles.

The insights from the interviews showed that changes are occurring in service provision regarding lighting, transport infrastructure and innovations related to mobiles, which are facing local challenges, such as the language diversity.

Overall, the investigation demonstrated that information collected at national level can reveal important insights on service provision. The quantitative part led to identifying long-term and aggregated trends, while the qualitative part brought insights from operations that are scaling up or service provision opportunities. However, the lack of service provision data for developing countries, such as Uganda, and the coverage of the household surveys, prevents insights being found across all services.

RQ 3: Where along the resource chains are energy policies focused both historically and at different country development levels?

After researching country conditions that provide well-being with resource transformations in Chapter 3, as well as conditions for service provision in a developing country in Chapter 4, it became clear that key stakeholders for service provision are in private and public sectors, where policies aim to transform and regulate the resource chain. Thus, the last research question focuses on characterising policies from a resource chain perspective for countries at different stages of development. This is the first time such characterisation has been undertaken. The characterisation is able to show where efforts have been focused over time, and is used to quantify the policy balances in different sectors and for categories beyond instruments. The characterisation serves as a stepping stone to understand policies from the systems perspective that many academics have called for.

From Chapter 2 policy research has focused on finding the right policy mixes and identifying dynamics that best suit the energy transition. However policy analyses hardly focus on understanding resource transformation, even when wide emission reductions could come from end-uses, and engineers hardly focus on policy analysis. Thus, Chapter 5 addressed this gap with a novel method of policy classification that relies on NLP and a kNN algorithm. The classification was used first to evaluate policy mixes from a sectoral perspective, and second to characterise the resource chain scope of global energy policies. The resource chain scope in each country was also shown along the development levels by creating interactive visualisation tools to explore the data and make observations.

The policy classification with the kNN algorithm had a prediction accuracy of 29-80%, depending on the number of labels to assign. The use of additional predictors for categories with high number of labels to assign resulted in higher prediction accuracy. Overall, the kNN model resulted useful for policy classification.

The policies studied were well-balanced across most sectors after 2005, whereas previous policies were unbalanced in the sectors of Households, Services, as well as General policies. This indicated that energy efficiency policies and the instruments typically used might not be sufficient for the required socio-technical transition.

The resource chain stages that are regulated in the policy database showed a shift of focus in the past two decades. European and North American policies showed a shift from the sectors of Buildings, Transport and Generation to an overwhelming number of policies focusing on the Buildings and Transport sectors. The shift reflects a move towards regulating activities closer to end-uses, which results in higher complexity in regulating each device type, leading to more policies being required. In countries at the lowest income levels, the results showed a prevalence for policies at the primary energy stage, with Sub-Saharan Africa presenting a shift from primary energy before 2010 to increasing final energy coverage, with more Buildings policies being created since 2010. Overall, the number of policies and sectors regulated in developing countries is growing. Overall, the required socio-technical transition in developed and developing countries needs many types of policies, including energy efficiency policies, the regulation beyond primary energy in developing countries and the regulation of industry in emerging and developing countries.

6.2 Wider implications

This section discusses the wider implications of the thesis dividing them into relevant topics and addressing how different stakeholders should consider such implications.

Focus on services and the devices that help provide them

This thesis evaluated some aspects of end-use devices: device ownership in Chapter 3 and device use in Chapter 4. This thesis found that there are varied dynamics in whether ownership of end-use devices can deliver higher levels of development, given the different correlation results using incumbent and replacement communication technologies in Chapter 3. Yet, the use of efficient devices is crucial if countries are to limit their climate impact and increase development, as shown by the low cooking stove efficiencies in Uganda in Chapter 4. Chapter 4 also showed that within a country context, device ownership increased with household expenditure levels and urbanisation, since increasingly different energy sources were used for the same service as expenditure grew. From a policy perspective, Chapter 5 showed that there is increasing policy complexity once technologies closer to end-uses are regulated, as highlighted by the high number of policies focusing on buildings and transport in the last decade (2010-2019). Further, end-uses in developing countries are starting to be regulated, such as the off-grid industry in Sub-Saharan Africa, but other efforts are still required, e.g. cooking, transport.

Chapters 3-5 showed that service provision through end-use device ownership should not be the only focus to increase well-being. Aspects related to the performance of devices, local contexts and practices, the conditions of those who use the devices, and implementing regulations should also be considered. Considering these aspects may also allow for more devices and stages of transformations to be added that challenge existing service provision systems, such as the mobile phone innovations in Uganda discussed in Chapter 4 or the disruptive low carbon innovations proposed by Wilson et al. (2019).

The paths to mitigate climate change require certain device-related practices to change. The changes include reaching technology maturity and large-scale deployment in innovation for the energy transition (Hart, 2020), the population's willingness to embrace change at the speed projected by models, and the creation of policies that support changes using the right instruments. It is therefore time-sensitive that energy transitions occur hand-in-hand with the different stakeholders involved. The peril of not taking the steps necessary involving devices is already exemplified by recent research by Kar et al. (2020), who record a high degree of adoption of an LPG cooking technology in India, but lower rates of regular use for the system.

Be aware of the pace of systemic change

This thesis has widely discussed changes over time in parts of the resource chain and how they impact well-being outcomes. Systems and the adoption of new practices, to a degree where it is noticeable in national indicators, tend to happen slowly. For instance, practice changes depended on finding reliable alternatives, and not only affordability as implied by results in Chapter 4. Thus, recognising and identifying the temporal variations of many indicators used in this thesis, may encourage policy makers to make decisions based on indicators that reflect both temporary and preserved gains in development or practice changes as discussed in Chapter 3.

Increasing levels of well-being depends on temporal dynamics, but the loss of those gains may happen in short periods of time. The World Bank (2020*a*) has observed the devastating effects of the COVID-19 pandemic and regional conflicts that will push 150 million people into extreme poverty by 2021. It then becomes clear that well-being gains made over decades may be eroded in a few months. This implies that both the energy transition and climate-compatible development require strategic plans to protect against any erosion of well-being gains.

Achieving climate-compatible development depends on the temporal dynamics of well-being levels and technology adoption. This is supported by Gross et al. (2018) who estimate that the development of technologies from conception to impacting emissions ranges from 20 to 70 years. This implication can inform policy makers, so policies to encourage rates of improvement of both factors are prioritised.

A shift of focus, away from only generation to resource transformations, is needed

This thesis has argued that resource transformations occur so services may be delivered, depending on local contexts, and has quantified the links between such resource transformations and well-being in Chapter 3, finding that data scarcity hinders efforts to understand service provision. Chapter 4 then presented a method to quantify resource transformations in countries where little data is available. Despite showing that the population could benefit from improvements in energy efficiency and emission reduction by addressing fuel stacking, many other services remain understudied. Chapter 5 then turned to energy policies and their inclusion of resource transformations, and demonstrated that the lack of systematic thinking of resource transformations is also hindering policy efforts. With the novel quantification of stages of the resource chain in energy policies, Chapter 5 showed there are efforts to regulate parts of the chain closer to services. These efforts are related to buildings and transport, but the efforts lag behind in low-income countries, whose energy policies are still mainly focused on primary energy.

The implications of Chapters 3-5 are that systematic approaches are needed to include resource transformations in country-level studies and policies. These will serve to guide efforts on energy transitions and development in all aspects, from engineering, to financing, to policies, among others discussed in Chapter 1. In particular low-income countries need to enhance their policy making processes to include end-use or services and not focus solely on energy generation, even if services are not considered a priority in the minds of policy makers.

6.3 Future work

Further research questions and research avenues stemming from this thesis are discussed in this section, first according to the future work identified around Chapters 3 to 5, followed by future work outside the main scope of this thesis.

Improving the understanding of services and the resource chain

As shown in Chapters 3 and 4, an effort is required from countries and institutions to gather necessary data to allow for service provision at different country levels to be calculated. Given the amount of data from several sources that was able to be amassed by this study that would not have been possible a few years ago, some, albeit insufficient, progress is being made. Increasing data availability could lead to analysing the situation for different regions or households within countries and compare them an an international scale. This would make conclusions more robust and account for inequalities within countries.

Among the indicators presented in Chapter 3, some can be improved and included in the regressions to extend the results, e.g. thermal comfort, communication and embodied emissions. Thermal comfort needs the addition of final energy data for heating and cooling, more detailed information on equipment used, and increasing country coverage. Communication as it stands is unable to account for information exchange, which, at least for telecommunications companies, is now collected, but not made publicly available. Total embodied emissions are closer to services than total emissions, because they consider the emissions embodied in domestic final demand. However, accounting them per resource chain transformations may produce more representative results. The available data is again a limitation regarding these suggestions.

This thesis showed that data for the resource chain rarely considers energy transformations until the end of the resource chain (useful energy or services). However, research in specific fields (e.g. transport) is much further ahead, while others are gaining momentum (e.g. cooling and cooking). Spreading information surrounding the end of the resource chain may show how resources are used and how they directly impact people's well-being. Future researchers could undertake regressions to identify drivers of more service provision indicators and countries. The research could also be expanded in future research to aggregate national data into relevant groups. Such analyses could highlight common drivers which could be used as levers for policy making.

Study the different dynamics of service provision and well-being, beyond the well-known saturation model

The correlations between service provision and well-being outcomes have been studied using a semi-logarithmic curve that reaches a saturation point, because many indicators such as total primary energy and total emissions fit such a curve. Chapter 3 showed that a saturation curve works well for some service provision indicators, but the inclusion of technological change and changes in service provision itself showed there are different dynamics to consider, beyond the semi-logarithmic curve. Other functional forms may be tested to study the relationship between the pairs of variables. An example may be a linear regression for GNI and primary energy, as hinted by their scatterplot. Thus, a technique such as the one presented by O'Neill et al. (2018) can be used, where several functional forms are explored for pairs of indicators and those with significant results are then presented.

The study of the dynamics of service provision can be completed over time for more indicators, years and countries than those included in Chapter 3. The methods used to improve the study of these dynamics can include other statistical analyses, such as panel data (e.g. as fixed effects), to be able to measure changes in a consistent way. Modifications of data inputs may also simplify comparisons, for example, using indices in service provision indicators to compare the magnitude and direction of the regressions consistently.

Incorporate the study of service provision for well-being into the broader narrative of well-being

The concept of well-being is closely aligned with development outcomes. However, there is an additional concept known as Quality of Life (Fuchs et al., 2020), which is being applied in a similar way as the other two concepts. Fuchs et al. (2020) highlight that political conditions should also be considered alongside social and economic factors when defining indicators to improve the Quality of Life. The analysis presented in Chapter 3 included social, economic, environmental and physical aspects of service provision. But indeed the political context of each country also alters the way service provision planning and service delivery are carried out. Therefore, there is an opportunity for inter-disciplinary work to be undertaken, where combined indicators across these fields are used.

Strategically assessing other countries and services to increase global data availability

Evaluating the impacts of changing fuel provision from both an energy and materials perspective, as well as their supply chains could further inform the work in Chapter 4. These types of analyses may benefit from pairing up the energy side with impacts of devices in environmental and health aspects, considering, for example, deforestation and smoke-related diseases and with infrastructure developments. Furthermore, as the statistical bodies of the country keep increasing the data available, other non-household services may be included, e.g. transport. Other assumptions that could be improved as more information becomes available are: the survey's non-unique allocations of end-uses for energy sources (e.g. kerosene is sometimes used for both cooking and lighting, but no break-down is reported or easily assumed).

The following recommendations involve changes to the way national household surveys are conducted: i) Prioritise the collection of energy source quantities used in surveys. Extend the information on generators to the list of energy sources given. ii) For the fuels of dung, solar and crop residue, create categories in the survey to expand on their energy use (e.g. for solar, ask about the number of lights and phone charging included, and what the system's power rating is). As for dung and crop residue, an estimation of volumes or mass may suffice to extend the calculations done in Chapter 4. iii) Include a list of type of devices and not only ownership. Given the current trends, it would be useful to know the type of lighting device used. iv) If global cooling trends are to affect the built environment, adding the type of cooling used at commercial and urban buildings might be valuable. v) Evaluate the breakdown of electricity by appliance by region or settlement to perform estimations of useful energy for other devices. There is potential to do this using Internet of Things devices, such as smart meters. vi) Extend the analysis to other sectors of the economy. For example, the same principle for calculating useful energy may be used for the industrial and commercial sectors.

The method developed in Chapter 4 to calculate useful energy can also be applied by experts working on improved cooking stoves, who tend to focus on final energy, e.g. the study of improved cooking in Benin, Uganda and India by Garland et al. (2015).

Extend NLP techniques in policy analysis

The policy classification presented in Chapter 5 is a novel use of NLP for classifying policies into parts of the resource chain, so the method can be further explored to improve predictions. If the kNN algorithm is to be used further, it can include adjustment to increase the prediction accuracy, such as exploring other predictors or reducing the number of labels to assign. The classification performance can also be studied introducing pre-trained word vectors, which are unsupervised learning algorithms made to contain some form of "meaning of words" by creating vector representations of words. The prediction accuracy can also be studied by including policy descriptions as predictors, however such an approach will be more data-intensive.

Other uses for the NLP method could be to create and update databases, and include additional or missing policy classifications. As for policy outcomes, NLP can be useful to track population reactions and sentiments once policies are in place. The NLP classification can also be combined with other policy analyses, e.g. innovation, and respond to the need for multi-technology, multi-country analyses, such as the one proposed by Bento et al. (2018). NLP could also facilitate analyses of investments and patents.

Increase policy analysis for service provision, including developing countries

The policy analysis for service provision included the classification of categories that could be used to study the policies further. For instance, the instruments used comparing the different stages of the chain might provide further insights. The data gathered for this thesis facilitates creating such an analysis.

Policy analysis for service provision in developing countries is hindered by the lack of data available to quantify the resource chain. This, along the traditional way of thinking of energy provision, in which well-being will be an extrinsic effect of increasing energy generation has likely led to developing countries focusing their energy policies mainly on generation as shown in Chapter 5. Thus, efforts to increase analyses of resource transformations focusing on services such as the one presented in Chapter 4 need to be presented to policy makers so the focus of policies begins to shift.

Expand the visualisation tool developed for policies and include statistical analyses

The policy and development visualisation tool developed and presented in Chapter 5 could be further improved to show not only the generic stages of the resource chain (i.e. primary, final, useful, service), but also present the names of the devices used - much like a Sankey diagram. This would further show the focus of policies.

The visualisation tool can also be used to answer additional research questions related to instruments, other regional classifications or regional policy balances. Other types of policies could also be tracked (e.g health). The additional research questions may also be complemented with statistical methods such as the ones used for econometrics to further quantify the influence of different variables.

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A

Additional information for regressions

A.1 Embodied carbon emissions calculation

The environmental outcomes were quantified as CO_2 emissions embodied in domestic final demand (C_{emb}) (the term 'embodied' should not be confused with the one used for CO_2 embodied in materials used in civil engineering). These values were recently incorporated to OECD statistics and they are calculated as shown in equation A.1. Since they are calculated according to demand, they are closely aligned to services.

$$C_{emb} = C_{domestic} + C_{imports} \tag{A.1}$$

Where: $C_{domestic}$ is the CO_2 emitted and consumed domestically and $C_{imports}$ is the CO_2 emitted abroad and embodied in imports.

A.2 Robust standard error regression

Heteroskedastic robust standard errors were used, after finding that the homoskedastic condition was not respected in the original OLS, using the HC3 estimator based on Mackinnon and White (1985) available in Python's statsmodels OLS. Since the sample size is important for robust standard errors, only the data with maximum number of countries will use this technique.

HC3 can keep the test size at the nominal level regardless of the presence or absence of heteroskedasticity and is thus recommended as the best option to use.

B

UNPS Survey data treatment and supplementary information

B.0.1 Data sources

- Uganda Bureau of Statistics. Uganda National Panel Survey (UNPS) 2009-2010. Ref. UGA_2009_UNPS_v01_M. Dataset downloaded from http://microdata.worldbank.org/index.php/catalog/1001 on 09/01/18.

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- Uganda Bureau of Statistics. Uganda National Panel Survey (UNPS) 2015-2016. Ref. UGA_2015_UNPS_v01_M. Dataset downloaded from https://microdata.worldbank.org/index.php/catalog/3460/get-microdata] on 31/05/19.

B.0.2 Energy used and energy measured

The percentage of households that use the given energy sources over the total number of households in the survey is shown in table B.1. Although the values presented here do not include any survey weighting, they can still be used for comparisons.

Fuel name	*Generally used*	*Cooking*	*Lighting*	*Heating*
Charcoal	27.3	27.2	0.1	1.4
Crop Residue	10.0	10.0	0.6	0.3
Dung	0.0	0.0	0.0	0.0
Electricity	12.9	1.0	12.9	0.6
Firewood	79.6	79.2	3.1	9.3
Kerosene	69.8	4.7	67.5	0.7
LPG	0.8	0.8	0.0	0.0
Solar	5.6	0.1	5.6	0.1

Table B.1 Percentage of households that use the given energy sources for named uses over the total households for UNPS 2013-2014.

B.0.3 Charcoal values used

Table B.2 shows the values considered for the calculations of charcoal-related quantities as reported in the National Charcoal Survey. The values were paired up with the information on the National Panel Survey based on regions to obtain more accurate estimations.

Region	*LHV (MJ/kg)*	*Mean weight of charcoal bag (kg)*	*Std (kg)*	*Min. weight of charcoal bag (kg)*	*Max. weight of charcoal bag (kg)*
Kampala	29.7	74.6	22.2	34.6	105.8
Central1	28.9	74.4	26.7	7.6	107.8
Central2	30.5	50.7	23.7	9.7	22.0
East Central	29.3	60.8	10.5	34.6	75.0
Eastern	29.3	97.0	53.4	48.8	164.4
Mid-North	29.6	54.2	13.2	20.1	75.6
North East	28.3	34.7	0.3	34.4	35.0
West Nile	30.0	63.4	21.8	32.9	104.0
Mid-West	30.9	52.2	18.2	8.1	78.0
South-western	30.5	48.9	8.2	38.3	78.3

Table B.2 Values used for mass and heating values of charcoal in Uganda as reported in the National Charcoal Survey.

B.0.4 Survey weights

The surveys contained information on household weights for the wave (year) and the panel. In our results, we used the weights for the wave that would be representative of Uganda's population in the given year. Overall, the survey was meant to be representative of the following regions: Kampala City, Other Urban Areas, Central Rural, Eastern Rural, Western Rural, and Northern Rural in the given year.

For the mean values calculated in the analysis (energy, expenditure, emissions), a weighted average was used, which considered the monthly quantity in question and the household weight. As for the shares of energy sources (presented below), the calculation was a little different to include the fraction of energy sources used.

Weights for energy source shares

Since households reported using several energy sources and the household weight, to calculate the shares of energy sources X_{f_i} in the country, the fraction of each source was considered in the calculation in the following way:

$$X_{f_i} = \frac{f_{i_{used}} w_{hh}}{\sum n_f \sum w_{tot}} \tag{B.1}$$

Where $f_{i_{used}}$ is the fuel when it was used with a value of 1, $\sum n_f$ is the sum of the number of fuels used, w_{hh} is the weight of each household and $\sum w_{tot}$ is the sum of households' weights

B.0.5 Expenditure deciles

The expenditure deciles per adult equivalent were calculated the following way: First, the total expenditure was obtained as the sum of expenditures in all given fields of the survey (durable, non-durable and other) and were converted to a monthly basis. Then, the expenditure values per household were divided by the number of adult-equivalents in each household. Finally, the values were split by deciles.

The number of adult equivalents per household refers to the number of adults and children converted, according to their age, to fractions of adult who are then aggregated. This treatment is common to account for age differences in the household members and it assumes that the variable in question, in this case, expenditure, has a different effect according to age. The adults equivalent *ad_eq* were calculated as equation B.2, where a refers to the age of household members and X are the household members.

$$ad\_eq = 0.2\, X_{a\leq 6} + 0.3\, X_{a>6,\, a\geq 12} + 0.5\, X_{a>12,\, a\leq 17} + X_{a>17} \tag{B.2}$$

B.0.6 Interview information

The interview protocol is described below, which included an introduction to this study, general questions surrounding the services of interest, and a discussion around topics relevant to the organisation.

Interview protocol

General introduction

Introduction to this study, the concept of services and the services relevant for Ugandan households e.g. sustenance, thermal comfort, communication, illumination.

General questions

The experts are asked to comment on their own experiences around the following questions:

- Which services, from the ones mentioned in the introduction to this interview, are most relevant for this organisation? How are they relevant?
- How does provision for the relevant service(s) occur?
- Which strategies are followed to deliver services relevant to the organisation?
- Which efforts do you consider to be required to improve service provision?
- What challenges are there in increasing service provision?

Additional questions depending on organisation

The experts are asked follow-up questions similar to the ones below:

- How is energy planning done? Which factors are considered?
- How are productive uses of energy considered? Which insights are available?
- What are users or customers preferences?

Closing remarks

Please indicate if any additional relevant information or database is available, based on the aims of this study.

C

Policy data

C.1 NLP for policy category classification

The data used contained different levels of information regarding each policy. Table C.1 shows the key categories used in the study and divides the information available by region to illustrate which regions and categories will require classification.

Table C.1 Sample size for each category where NLP classifications were used.

		Sector		Technology		Topic		Type		End-use	
Region	Total n	Available n	Missing n	Available n	Missing n	Available n	Missing n	Available n	Missing n	Available n	Missing n
AFR	348	244	104	233	115	276	72	336	12	61	287
CPA	545	261	284	243	302	289	256	515	30	138	407
EEU	925	878	47	247	678	321	604	887	38	124	801
EU	2133	173	1960	100	2033	115	2018	234	1899	100	2033
FSU	204	159	45	127	77	166	38	195	9	91	113
GLOB	3	0	3	0	3	3	0	3	0	0	3
LAC	770	474	296	439	331	517	253	747	23	208	562
MEA	285	137	148	127	158	151	134	281	4	56	229
NAM	1234	972	262	843	391	1002	232	1218	16	740	494
PAO	551	404	147	343	208	445	106	530	21	274	277
PAS	617	260	357	251	366	299	318	605	12	153	464
SAS	252	194	58	166	86	206	46	240	12	125	127
WEU	2950	2685	265	1323	1627	1808	1142	2834	116	1019	1931

C.1.1 Additional information for the k Nearest Neighbours (kNN) algorithm

To implement the policy classification, the python libraries of spacy, scikit learn and nltk were used, including a Tfidf vectoriser and the KNeighborsClassifier from scikit learn. Additionally, to save and use the model for the database with unclassified categories, the python libraries of pickle was used.

In the kNN models developed to classify policy categories, the following final parameters were used: number of neighbours (k) = 10, weights = ‘distance’, random_state = 13. Variations of k were studied to obtain values at the highest possible accuracy. The test size (s) was varied for each category model from 0.1 to 0.9 to find the one that produced the highest accuracy before finalising the model and applying it to the whole dataset.

Accuracy of kNN models tested

The models tested for each category included varying k and s to see the effect on accuracy.

Figure C.1 shows the variations of s and the prediction accuracy obtained using $k = 10$. For both the lowest and highest number of unique labels that need to be assigned, the highest number of samples (90%) produced the highest accuracy. The rest of the categories required 70-80% of the dataset to produce results at their highest-possible accuracy.

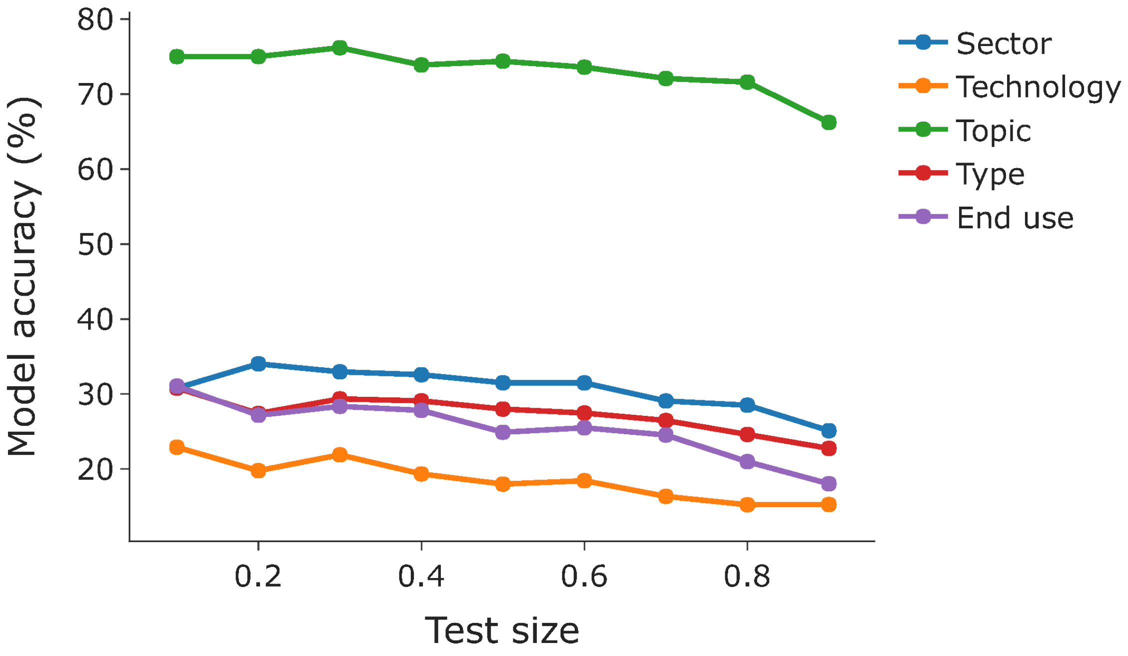

Fig. C.1 Tested models variation of accuracy depending on sample size used.

C.2 Resource chain classification using technologies

Technology	Chain classification
2 wheelers	Final, Useful, Service
3 and 4 wheelers	Final, Useful, Service
3 wheelers	Final, Useful, Service
Active transport	Final, Useful, Service
Aerodynamics	Final, Useful, Service
Aerothermal heat pump	Final, Useful, Service
Air leakage	Useful, Service
Air transport technologies	Final, Useful, Service
Appliances	Final, Useful
Audiovisual	Final, Useful, Service
Batteries	Final, Storage, Final 2
Battery electric	Final, Storage, Final 2, Useful, Service

Bioenergy with carbon capture and storage	Source, Primary, Final
Biogas boiler	Final, Useful
Biogas powerplant	Source, Primary, Final
Biomass boiler	Final, Useful
Biomass powerplant	Source, Primary, Final
Blowdown capture	Final, Useful, Service
Boilers	Final, Useful, Service
Boilers (industrial)	Final, Useful, Service
Building envelope	Useful, Service
Building systems	Useful, Service
Building technologies	Useful, Service
Building vintage	Useful, Service
Buses	Final, Useful, Service
Central HVAC	Final, Useful, Service
CHP	Source, Primary, Final
CO2 capture technology	Final, Useful, Service
CO2 Storage	Final, Useful, Service
CO2 Transportation	Final, Useful, Service
CO2 Utilisation	Final, Useful, Service
Coal boilers	Final, Useful, Service
Commercial vehicles	Final, Useful
Compact fluorescent lamp	Final, Useful, Service
Compression ignition (diesel)	Final, Useful
Compressors	Final, Useful, Service
Computer	Final, Useful, Service
Conventional gas boilers	Final, Useful, Service
Cooking	Final, Useful, Service
Cooling fan	Final, Useful, Service
Direct air capture (DAC)	
Dishwasher	Final, Useful, Service
Distribution transformers	Final, Useful, Service
District cooling	Final, Useful, Service
District heating	Final, Useful, Service, Useful
Doors	Final, Useful, Service
Dryer	Final, Useful, Service
Electric charging infrastructure	Final, Storage, Final 2

Electric chillers	Final, Useful, Service
Electric cooker	Final, Useful, Service
Electric heat pumps	Final, Useful, Service
Electric instantaneous heaters	Final, Useful
Electric radiator	Final, Useful
Energy class	Final, Useful, Service
Energy management systems (buildings)	Final, Useful, Service
Energy management systems (Industry)	Final, Useful, Service
Enhanced oil recovery (EOR)	Source, Primary
Existing buildings	Useful, Service
Exterior lighting	Final, Useful, Service
External power supplies	Final, Useful, Service
Fast chargers	Final, Useful, Service
Fenestration	Final, Useful, Service
Fittings and controls	Final, Useful, Service
Flares	Final, Useful, Service
Floor insulation	Useful, Service
Fluorescent lamp	Final, Useful, Service
Freezer	Final, Useful, Service
Freight rail	Final, Useful, Service
Freight shipping	Final, Useful, Service
Fuel cell	Final, Useful, Service
Gas heat pumps	Final, Useful, Service
Gas instantaneous boilers	Final, Useful, Service
Gas Stoves	Final, Useful, Service
Geothermal	Source, Primary, Final
Geothermal electricity	Final, Useful, Service
Geothermal heat	Source, Final, Useful
Geothermal heat pump	Final, Useful, Service
Ground-source AC	Final, Useful, Service
Halogen	Final, Useful, Service
Heat pumps	Final, Useful, Service
Heavy trucks	Final, Useful, Service
High-intensity discharge lamps	Final, Useful, Service
Humidification	Final, Useful, Service
HVAC	Final, Useful, Service

Hybrid	Final, Useful, Service
Hydropower	Source, Primary, Final
Hydropower run of river	Source, Primary, Final
Incandescent	Final, Useful, Service
In-car feedback	Final, Useful
Incinerator	Final, Useful, Service
Industrial equipment	Final, Useful
Industrial processes	Primary, Final, Useful
Industrial products	Final, Useful, Service
Industry technologies	Final, Useful
Insulation	Final, Useful, Service
Intelligent transportation (for freight)	Final, Useful
Interior lighting	Final, Useful, Service
Internal combustion engine (ICE)	Final, Useful, Service
Lamp technologies	Final, Useful, Service
Large scale biomass boiler	Final, Useful, Service
LDAR annually	Final, Useful, Service
LDAR bi-annually	Final, Final 2
LDAR quarterly	Final, Useful, Service
LDAR tri-annually	Final, Useful, Service
LDAR-downstream	Final, Useful, Service
LDAR-upstream	Final, Useful, Service
Light commercial vehicles	Final, Useful, Service
Light emitting diode	Final, Useful, Service
Lighting	Final, Useful, Service
Linear fluorescents	Final, Useful, Service
Low energy	Final, Useful, Service
Marine energy	Source, Primary, Final
Mass passenger transport chargers	Final, Storage, Final 2
Mass transport	Final, Useful, Service
Medium trucks	Final, Useful, Service
Miscellaneous	Final, Useful, Service
Modern Biomass stoves	Source, Useful, Service
Modern solid biomass boilers	Final, Useful, Service
Motor-driven systems	Final, Useful
Motors	Final, Useful, Service

Multiple renewable technologies	Source, Primary, Final
Multiple technologies	Source, Primary, Final
Net zero energy	Final, Useful, Service
New buildings	Useful, Service
Offgrid PV	Final, Useful, Service
Office equipment	Final, Useful, Service
Oil boilers	Final, Useful, Service
Oil stoves	Primary, Final, Useful, Service
On-street chargers	Final, Storage, Final 2
Other (building class)	Useful, Service
Other (non-engine component)	Final, Useful, Service
Other Cooking	Final, Useful, Service
Other exterior lighting	Final, Useful, Service
Other IT	Final, Useful, Service
Other plugloads	Final, Storage, Final 2
Passenger aircraft	Final, Useful, Service
Passenger car	Final, Useful, Service
Passenger light truck	Final, Useful, Service
Passenger light-duty vehicle	Final, Useful, Service
Passenger vehicles	Final, Useful, Service
Pellet stove	Primary, Final, Useful, Service
Plug loads	Final, Storage, Final 2
Plug-in hybrid	Final, Storage, Final 2, Useful, Service
Private chargers	Final, Useful, Service
Process heat	Final, Useful, Service
Public chargers	Final, Useful, Service
Pumps	Final, Useful, Service
PV Ongrid	Final, Useful, Service
PV Residential	Source, Primary, Final
Rail transport technologies	Final, Useful, Service
Reduced Emission Completion	Final, Useful, Service
Refrigerator	Final, Useful
Replace compressor seal or rod	Final, Useful, Service
Replace pumps	Final, Useful, Service
Replace with electric motor	Final, Useful
Replace with instrument air systems	Final, Useful, Service

Resistive heaters	Final, Useful, Service
Road transport technologies	Final, Useful
Roof insulation	Useful, Service
Room AC	Final, Useful
Shading	Final, Useful, Service
Skylights	Final, Useful, Service
Slow chargers	Final, Useful, Service
Small electronic devices	Final, Useful
Smart meters	Final, Final 2
Solar	Source, Primary, Final
Solar cooling	Primary, Final, Useful, Service
Solar home systems	Primary, Final, Storage, Final 2
Solar PV	Primary, Final, Storage, Final 2
Solar space heater	Final, Useful, Service
Solar thermal	Source, Primary, Final, Useful
Solar thermal electricity (CSP)	Final, Useful, Service
Solar thermal heaters	Final, Useful, Service
Space and water heating tech	Final, Useful
Space cooling	Final, Useful, Service
Split AC	Final, Useful, Service
Standby power	Final, Useful, Service
Street lighting	Final, Useful, Service
Television	Final, Useful, Service
Thermostat	Final, Final 2
Tidal energy	Final, Useful, Service
Transport infrastructure technologies	Useful, Service
Transport technologies	Final, Useful
Tyres	Final, Useful, Service
Vapour recovery units	Final, Useful, Service
Vehicle (engine)	Final, Useful
Vehicle (non-engine)	Final, Useful, Service
Vehicle technologies	Final, Useful
Ventilation	Useful, Service
Wall insulation	Useful, Service
Washing machine	Final, Useful, Service
Water heating	Final, Useful

Water transport technologies	Final, Useful, Service
Wave energy	Final, Useful, Service
Wind	Source, Primary, Final
Wind offshore	Source, Primary, Final
Wind onshore	Source, Primary, Final
Windows	Useful, Service