Guiding progress towards sustainable energy access for all: multi-dimensional metrics and equitable energy service provision

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Preface

This dissertation was written under the regulations for publication-based *'cumulative'* dissertations at the Europa-Universität Flensburg (EUF). The EUF regulations assigned points for each paper based on the total number of co-authors. The points are calculated as follows: 2/(Authors+1). A total of three points were necessary to satisfy the minimum requirements for submission. One article was to be sole-authored. All articles were required to be published prior to submission. These requirements are met in this work with the publication of six first-author articles. Beyond the requirements set out in the EUF regulations, this dissertation includes a narrative summary in the main text, drawing selectively from the detailed and extensive work conducted within the articles themselves. This narrative summary is complementary to the six articles included as appendices to the main text. The dissertation should thus be examined in its entirety, that is, the narrative summary presented in the main text should be reflected upon alongside the articles themselves, which represent the actual body of work. Finally, the narrative summary is written as a collection of R Markdown scripts using the Thesisdown template. These scripts reference the actual datasets analysed in preparing all of the analysis, figures and tables presented in the narrative summary, except for those refering to the work of other authors or where specifically clarified. The analysis and results are therefore replicated anew using the raw data each time this document is compiled.

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Dedication

I dedicate this work to my parents, Nilima and Dieter, and my brother, Theo.

Executive Summary

This dissertation explores the measurement of energy access and energy poverty, and its role in guiding policies to facilitate universal and equitable energy access. This is a cumulative dissertation and is therefore presented in two parts. Six peer-reviewed papers comprise the body of work and are presented in full in the appendices. The narrative summary, presented in the main text, guides the reader through the work conducted and describes the main findings and arguments that this dissertation seeks to defend.

Household access to modern energy services is considered the cornerstone of achieving several of the goals defined under the United Nation's Sustainable Development Goals (SDG). 789 million people around the world still lack access to electricity, while 2.8 billion continue to cook meals and heat their homes with biomass fuels. Efforts to improve on this deficit are guided by SDG Target 7.1: *"ensure universal access to affordable, reliable and modern energy services."* (SDG Target 7.1). Despite the rich wording of the SDG target 7.1, progress is measured and guided by binary indicators that only capture connection to a modern energy source.

The work begins by establishing the moral motivation for achieving SDG target 7.1 from the perspective of the Capabilities Approach. That is, the prime motivation for providing access to modern energy services is the freedoms they offer and the capabilities they provide households. This formal motivation is translated into practical measurement by examining the energy requirements this would entail. This draws from the material requirements to satisfy basic needs as defined under the Decent Living Standards. Elements of contemporary Energy Justice theory are then introduced to move from the evaluation of inequities towards reform. These three concepts collectively form the theoretical foundation that scaffolds all of the subsequent work.

Guided by this theoretical foundation, the work questions the status-quo of energy access measurement along two lines: First, the inadequacy of binary connection-based indicators for measuring progress towards SDG Target 7.1.; and second, the limitations of contemporary multi-dimensional measurement frameworks that could replace them. From a justice perspective, there is a clear mismatch between current connection-based indicators and the wording of SDG target 7.1. The current indicators do not capture reliability or affordability of supply, nor do they address household access to modern *energy services* (such as lighting and cooling). A critical evaluation of contemporary multi-dimensional measures showcases immense progress in our conceptual understanding of energy access measures. However, it also finds

rigid assumptions and severe limitations in the design of the leading measurement approach, the Multi-Tier Framework (MTF).

The assumptions and limitations of the MTF are first tested through econometric analysis of secondary household and enterprise survey data from rural northern India. The MTF disaggregates energy access across a series of distinct attributes. It then reduces it into an aggregate tier by the lowest performing attribute, assuming all attributes to be equal. Rejecting this assumption, the empirical work shows that the distinct attributes of electricity supply are heterogeneously linked to energy service utilisation. The MTF also presents a pragmatic focus on supply, and implicitly ranks appliances by power consumption rather than a theory of basic needs. The empirical work shows that while supply measurement is a crucial aspect of understanding bottlenecks requiring policy and regulatory intervention, household access to a basic set of energy services, (the desired goal of energy provision), hinges on a broad range of factors and cannot be assumed to occur even if the household is provided reliable access to electricity. The results are then considered in the context of productive electricity use among Micro- and Small Enterprises (MSEs) also in the same region of rural northern India. The empirical work shows that electricity usage across this sample of rural MSEs is likely to be strongly modified by wealth constraints rather than grid supply reliability constraints. Moreover, actual use of electricity both in terms of energy services and electricity consumption is quite low. As with the household survey analysis outcomes, it appears that reliable electricity supply to rural firms should not be conflated with usage. This points once again towards the need to capture both supply, as well as usage and related capabilities in future measurement frameworks.

This leads to two central propositions in this work. First, distinct attributes of supply should not be aggregated by the lowest performing attribute. Rather, energy supply should be assessed across distinct irreducible attributes until a sound justification for weighted aggregation based on household preferences is established in the given context. Second, it is imperative that measures also reflect the satisfaction of the basic needs linked with household freedoms and capabilities, given that this satisfaction is the ultimate goal of energy service provision. It is therefore necessary to establish measures capable of guiding policy intervention to both sides of the energy system - energy supply and satisfaction of basic needs.

These two propositions inform a case study describing the data collection and analysis of energy supply and usage inequities across municipalities with limited available socio-economic, demographic and other relevant data in rural Nepal. This case study identifies severe wealth and geographic disparity within and across the surveyed municipalities. Notably, the severity and the extent of inequities in energy service access far outweigh those in terms of electricity supply. This indicates that policy intervention must shift from a supply-focus towards also understanding barriers preventing poorer households from acquiring appliances necessary to satisfy basic needs. The challenges observed underline once again that both distinct attributes of supply and satisfaction of basic energy services must be captured in order to inform equitable progress across the full income distribution.

The preceding theoretical arguments and empirical findings then inform the development of an Alternative Framework (AF) for measuring progress towards target SDG

7.1, addressing the limitations described above. This expands on the prior work of co-authors and describes a framework for capturing distinct attributes of supply and utilisation, aligned with the material requirements stipulated under the Decent Living Standards. The AF is applied to recent household survey data from ten countries and compared against the current indicators for SDG target 7.1. The results reveal severe deficits in affordable and reliable access to modern energy services among households considered 'served' by the current indicators. Moreover, these deficits appear to be systematically associated with household wealth, such that poorer households considered served under the current SDG target 7.1 indicators are less likely to have affordable and reliable access to modern energy services. This puts forward a strong empirical case supporting the theoretical concerns raised in the earlier pieces of work with respect to measures for guiding equitable progress for all segments of the population. The AF and its application serve as a clear and direct provocation for further discussion into how target SDG 7.1 is measured. Notwithstanding limitations in the definition of thresholds across the selected attributes, the AF is arguably the most complete representation of SDG target 7.1 in indicator form. As thoughts turn to evaluation of progress along the SDGs as well as the global post-2030 agenda, it is hoped that this finding sparks serious discussion.

Finally, the sub-national perspective is considered through a case-study of energy supply provision among marginalised populations in rural northern India. This case study demonstrates the importance of multi-dimensional measurement as a control for institutional and governance weaknesses that can reinforce historical socio-cultural inequities as energy access rates (i.e., connections) improve. The results complicate the rapid progress reported following pro-poor energy policy reform in rural northern India. Measured as typical hours of supply for electricity, and home delivery of LPG for clean cooking, the results describe inequities in the associated quality of energy supply. In short, it appears that a focus on connections insufficiently controls for state-level institutional capacity constraints to the detriment of supply quality for marginalised communities. The resulting inequities are entirely masked by aggregate access rates that paint a picture of progress for the population as a whole. The results reinforce the earlier findings. It is crucial that energy access measurement captures clearly defined, irreducible attributes, in order to control for institutional weaknesses which may negatively modify the implementation of progressive policy reform.

In summary, this research project joins a chorus of recent scholarship arguing for improvement to SDG target 7.1 indicators and national-level data collection efforts to inform real progress towards universal and equitable energy access. The theoretical and empirical contributions described here are not without their own limitations. Nonetheless, it is hoped that the distinct papers influence and contribute to the transition towards a more egalitarian distribution of energy infrastructure and access to energy services necessary to achieve a decent living standard for all.

Zusammenfassung

Diese Dissertation untersucht die Messung des Energiezugangs und der Energiearmut und ihre Rolle bei der Gestaltung von Maßnahmen zur Förderung eines allgemeinen und gerechten Energiezugangs. Dies ist eine kumulative Dissertation und wird daher in zwei Teilen vorgelegt. Sechs peer-reviewed Artikel bilden den Hauptteil der Arbeit und werden in den Anhängen vollständig vorgestellt. Die im Haupttext dargestellte Zusammenfassung bietet eine Einführung in die durchgeführten Arbeiten und beschreibt die wichtigsten Ergebnisse und Argumente, die in dieser Dissertation vertreten werden sollen.

Zugang zu moderner Haushaltsenergieversorgung wird als Eckstein zur Verwirklichung mehrerer Ziele betrachtet, die im Rahmen der nachhaltigen Entwicklungsziele der Vereinten Nationen (Sustainable Development Goals, SDG) festgelegt wurden. 789 Millionen Menschen auf der Welt haben immer noch keinen Zugang zu Elektrizität, indessen kochen und heizen 2,8 Milliarden Menschen weiterhin mit Biomasse. Bemühungen um eine Verbesserung dieses Defizits orientieren sich an dem folgenden Teilziel: *"Sicherstellung des Zugangs zur erschwinglichen, zuverlässigen, nachhaltigen und modernen Energie fuer Alle"* (SDG-Ziel 7.1). Trotz der ausführlichen Formulierung des SDG-Ziels 7.1 wird der Fortschritt anhand von Indikatoren gemessen, die nur den Anschluss an eine moderne Energiequelle erfassen.

Die Arbeit beginnt mit der Festlegung der moralischen Motivation für die Erreichung des SDG-Ziels 7.1 hinsichtlich des "Capabilities Approach." Das heißt, die Hauptmotivationen für die Gewährleistung des Zugangs zu moderner Energieversorgung sind die Freiheiten und die Möglichkeiten, die sie den Haushalten bieten. Diese formale Motivation wird in praktische Maßnahmen umgesetzt, indem der damit verbundene Energiebedarf untersucht wird. Dabei wird von den materiellen Anforderungen zur Befriedigung der Grundbedürfnisse ausgegangen, wie sie im Rahmen der Decent Living Standards definiert sind. Anschließend werden Elemente der modernen Theorie der Energiegerechtigkeit eingeführt, um von der Bewertung der Ungleichheiten zur Reform überzugehen. Diese drei Konzepte bilden zusammen das theoretische Fundament, auf dem die gesamte weitere Arbeit aufbaut.

Ausgehend von dieser theoretischen Grundlage stellt die Arbeit den Status Quo der Messung des Energiezugangs in zweierlei Hinsicht in Frage: Erstens die Unangemessenheit binärer Indikatoren für die Messung des Fortschritts bei der Erreichung des SDG-Ziels 7.1. und zweitens die Grenzen moderner multidimensionaler Messrahmen, die sie ersetzen könnten.

Aus der Perspektive der Gerechtigkeit ergibt sich eine klare Diskrepanz zwischen

den derzeitigen auf Energieanschluss basierenden Indikatoren und dem Wortlaut des SDG-Ziels 7.1. Die aktuellen Indikatoren erfassen weder die Zuverlässigkeit oder die Bezahlbarkeit der Versorgung noch den Zugang der Haushalte zu moderner *Energy Services* (wie Licht und Kühlung). In ähnlicher Weise zeigt eine kritische Bewertung der modernen mehrdimensionalen Messrahmen einen immensen Fortschritt in unserem konzeptionellen Verständnis von Energiezugangsmaßnahmen. Allerdings werden auch starre Annahmen und schwerwiegende Einschränkungen in der Konzeption des führenden Messrahmens, des Multi-Tier Framework (MTF), festgestellt.

Die Annahmen und Grenzen des MTF werden zunächst durch eine ökonometrische Analyse sekundärer Haushalts- und Unternehmensumfragedaten aus dem ländlichen Nordindien getestet. Die MTF disaggregiert den Energiezugang über eine Reihe von verschiedenen Attributen. Die Energiezugang wird anhand des am schlechtesten abschneidenden Attributs auf eine aggregierte Ebene reduziert, wobei angenommen wird, dass alle Attribute gleich sind. In Ablehnung dieser Annahme zeigt die empirische Arbeit, dass die verschiedenen Attribute der Elektrizitätsversorgung in heterogener Weise mit der Nutzung von Energiedienstleistungen verbunden sind. Das MTF legt außerdem einen pragmatischen Schwerpunkt auf die Versorgung und ordnet die Haushaltsgeräte implizit nach dem Stromverbrauch und nicht nach einer Theorie der Grundbedürfnisse. Die empirische Arbeit zeigt, dass die Messung der Versorgung zwar ein entscheidender Aspekt für das Verständnis von Engpässen ist, die ein Eingreifen der Politik und der Regulierungsbehörden erfordern, dass aber der Zugang der Haushalte zu einer Grundausstattung an Energy Services (das angestrebte Ziel der Energieversorgung) von einer Vielzahl von Faktoren abhängt, und nicht einmal dann angenommen werden kann, wenn den Haushalten ein zuverlässiger Zugang zu Strom gewährt wird.

Die Ergebnisse werden dann im Zusammenhang mit der produktiven Stromnutzung von Kleinst- und Kleinunternehmen (KKU) in derselben Region des ländlichen Nordindiens betrachtet. Die empirische Arbeit zeigt, dass die Stromnutzung in dieser Stichprobe ländlicher KKU wahrscheinlich eher durch Wohlstandsbeschränkungen als durch Beschränkungen der Zuverlässigkeit der Netzversorgung beeinflusst wird. Darüber hinaus ist die tatsächliche Nutzung von Strom sowohl im Hinblick auf Energiedienstleistungen als auch auf den Stromverbrauch recht gering. Es scheint, wie bei den Ergebnissen der Haushaltsbefragung, dass die zuverlässige Stromversorgung ländlicher Unternehmen nicht mit der Nutzung gleichgesetzt werden sollte. Dies weist erneut auf die Notwendigkeit hin, in künftigen Messrahmen sowohl die Versorgung als auch die Nutzung und die damit verbundenen Fähigkeiten zu erfassen.

Dies führt zu zwei zentralen Thesen in dieser Arbeit. Erstens sollten verschiedene Versorgungsattribute nicht nach dem am schlechtesten abschneidenden Attribut aggregiert werden. Vielmehr sollte die Energieversorgung anhand verschiedener irreduzibler Attribute bewertet werden, bis eine stichhaltige Begründung für eine gewichtete Aggregation auf der Grundlage der Präferenzen der Haushalte im gegebenen Kontext gefunden wird. Zweitens ist es zwingend erforderlich, dass die Massnahmen die Befriedigung der Grundbedürfnisse in Verbindung mit den Freiheiten und Fähigkeiten der Haushalte widerspiegeln, zumal dass das letztendliche Ziel der Bereitstellung von

Energiedienstleistungen diese Befriedigung sei. Es ist daher notwendig, Messrahmen festzulegen, die dazu geeignet sind, Maßnahmen auf beiden Seiten des Energiesystems - Energieversorgung und Befriedigung der Grundbedürfnisse - zu steuern.

Diese beiden Thesen bilden die Grundlage für eine Fallstudie, in der die Datenerhebung und Analyse von Ungleichheiten bei der Energieversorgung und -nutzung in Gemeinden mit begrenzten sozioökonomischen, demografischen und anderen relevanten Daten im ländlichen Nepal beschrieben wird. Diese Fallstudie zeigt, dass Ungerechtigkeiten bei der Energieversorgung und -nutzung im Hinblick auf Wohlstands- und geografische Ungleichheiten innerhalb und zwischen den untersuchten Gemeinden festgestellt werden können. Insbesonders überwiegen die Schwere und das Ausmaß der Ungleichheiten beim Zugang zu Energy Services bei weitem jene bei der Stromversorgung. Dies deutet darauf hin, dass sich die politischen Eingriffe nicht nur auf die Versorgung konzentrieren sollten, sondern auch Verständniss für die Hindernisse aufbringen, die ärmere Haushalte daran hindern, die für die Befriedigung der Grundbedürfnisse erforderlichen Geräte zu erwerben. Die beobachteten Herausforderungen unterstreichen einmal mehr, dass sowohl unterschiedliche Attribute des Versorgungs- als auch des Zugangs zu grundlegenden Energiedienstleistungen erfasst werden müssen, um über gerechte Fortschritte über die gesamte Einkommensverteilung hinweg informieren zu können.

Die vorangegangenen theoretischen Argumente und empirischen Ergebnisse bilden dann die Grundlage für die Entwicklung eines Alternative Framework (AF) zur Messung des Fortschritts in Richtung des SDG 7.1 Zieles, das die oben beschriebenen Einschränkungen berücksichtigt. Dies erweitert die frühere Arbeit anderer Co-Autoren und beschreibt einen Rahmen für die Erfassung verschiedener Attribute des Versorgungs und Nutzungsgrades, der sich an den Decent Living Standards orientiert. Das AF wird auf aktuelle Haushaltserhebungsdaten aus zehn Ländern angewandt und mit den aktuellen Indikatoren für das SDG-Ziel 7.1 verglichen. Die Ergebnisse zeigen gravierende Defizite beim bezahlbaren und zuverlässigen Zugang zur modernen Energieversorgung bei Haushalten, die nach den aktuellen Indikatoren als 'versorgt' gelten. Darüber hinaus scheinen diese Defizite systematisch mit dem Wohlstand der Haushalte zusammenzuhängen, so dass ärmere Haushalte, die nach den aktuellen Indikatoren für das SDG-Ziel 7.1 als versorgt gelten, seltener einen bezahlbaren und zuverlässigen Zugang zu modernen Energiedienstleistungen haben. Dies ist ein starkes empirisches Argument, das die theoretischen Bedenken untermauert, die in den früheren Arbeiten im Hinblick auf Messrahmen zur Steuerung eines gerechten Fortschritts für alle Bevölkerungsgruppen geäußert wurden. Der AF und dessen Anwendung dienen als klare und direkte Aufforderung zur weiteren Diskussion darüber, wie das SDG 7.1 gemessen werden kann. Ungeachtet der Einschränkungen bei der Definition von Grenzwerten für die ausgewählten Attribute ist der AF wohl die vollständigste Darstellung des SDG-Ziels 7.1 in Form von Indikatoren. Im Hinblick auf die Bewertung der Fortschritte bei den SDGs und der globalen Agenda für die Zeit nach 2030 ist zu hoffen, dass dieses Ergebnis eine ernsthafte Diskussion auslöst.

Schließlich wird die subnationale Perspektive anhand einer Fallstudie zur Energieversorgung marginalisierter Bevölkerungsgruppen im ländlichen Nordindien betrachtet. Diese Fallstudie zeigt, wie wichtig eine mehrdimensionale Messung ist, um institutionelle Schwächen zu kontrollieren, die historische soziokulturelle Ungleichheiten verfestigen können, wenn sich die Energiezugangsraten (d. h. die Anschlüsse) verbessern. Die Ergebnisse relativieren die raschen Fortschritte, die nach der Reform der Energiepolitik zugunsten der Armen im ländlichen Norden Indiens gemeldet wurden. Gemessen an den typischen Versorgungsstunden für Strom und der Lieferung von LPG zum sauberen Kochen beschreiben die Ergebnisse Ungleichheiten in der damit verbundenen Qualität der Energieversorgung. Kurz gesagt, es hat den Anschein, dass die Fokussierung auf Anschlüsse die institutionellen Kapazitätsbeschränkungen auf staatlicher Ebene nur unzureichend berücksichtigt, was zu Lasten der Versorgungsqualität für marginalisierte Gemeinschaften geht. Die sich daraus ergebenden Ungleichheiten werden durch die aggregierten Zugangsraten, die ein Bild des Fortschritts für die Gesamtbevölkerung zeichnen, völlig verdeckt. Die Ergebnisse bekräftigen die früheren Erkenntnisse. Es ist von entscheidender Bedeutung, dass bei der Messung des Energiezugangs klar definierte, nicht reduzierbare Attribute erfasst werden, um institutionelle Schwächen zu kontrollieren, die die Umsetzung progressiver politischer Reformen negativ beeinflussen können.

Zusammenfassend schließt sich dieses Forschungsprojekt einer Reihe neuerer wissenschaftlicher Arbeiten an, die für eine Verbesserung der Indikatoren für das SDG-Ziel 7.1 und der Datenerhebung auf nationaler Ebene plädieren, um echte Fortschritte auf dem Weg zu einem universellen und gerechten Energiezugang zu erzielen. Die hier beschriebenen theoretischen und empirischen Beiträge sind nicht ohne ihre eigenen Einschränkungen. Dennoch ist zu hoffen, dass die einzelnen Artikel den Übergang zu einer egalitäreren Verteilung der Energieinfrastruktur und des Zugangs zu Energiedienstleistungen, die zur Erreichung eines angemessenen Lebensstandards für alle notwendig sind, beeinflussen und dazu beitragen.

Introduction

Household access to modern energy services is considered the cornerstone of achieving several of the goals defined under the United Nation's Sustainable Development Goals (McCollum et al., 2018; Nerini et al., 2017; Riva, Ahlborg, Hartvigsson, Pachauri, & Colombo, 2018; UN, 2015). 789 million people around the world still lack electricity, while 2.8 billion continue to cook meals and heat their homes with biomass fuels in open fires (IEA, IRENA, UNSD, World Bank, WHO, 2020). A much larger share of the world's population faces unreliable electricity supply and inconsistent usage of cleaner cooking fuels (Ayaburi, Bazilian, Kincer, & Moss, 2020; ESMAP and GACC, 2020). The global energy access discourse, however, continues to focus on connections. There exists a real risk that inequities in supply quality and well-being improvements associated with energy consumption will persist, or even widen, if left unchecked. Motivated by this shadow deficit, this research project explores the measurement of energy access/poverty and the role this plays in guiding equitable progress towards universal energy access from a justice-based perspective. This is a publication-based research project and is thus comprised of six peer reviewed papers and a narrative summary presented in the main text here. The narrative summary functions as a synthesis and introduction to the six papers, which are included in the appendices and complete the body of work.

The first chapter begins with introducing the theoretical foundation guiding the work conducted. The empirical approach and data used in each of the six papers is then briefly discussed. The theoretical foundation draws from the Capabilities Approach, Decent Living Standards and elements of contemporary Energy Justice literature. I collectively term these *'justice-based'* approaches for reference later in this work. The Capabilities Approach links energy services with the freedoms they offer and capabilities they provide households, establishing a moral imperative for energy service provision. The Decent Living Standards create a bridge from the moral imperative of energy service provision to its practical implementation in energy poverty measurement. Energy Justice concepts then provide the framework necessary for moving from measuring inequities towards alleviating these through policy, procedural and governance changes. The empirical work is largely grounded in econometric analysis methods, using both primary and secondary survey data. The work remains descriptive in nature and focuses on describing relationships, trends and differences across groups and over time. Figure 1 provides a graphical abstract of the theoretical discussion and can aid in understanding how these distinct concepts are connected.

The second chapter provides a critical analysis of how multi-dimensional energy poverty is currently measured in light of sustainable development goal 7.1: *"By 2030, ensure universal access to affordable, reliable and modern energy services"* (SDG 7.1). It begins with describing the evolution of the definition of household energy services and multi-dimensional energy access measurement. The three primary frameworks for multi-dimensional energy access measurement are then critically evaluated. Their usefulness in informing equitable policy development and agenda setting at the national and global levels is discussed and ways forward to improve on this are proposed. Specifically, the limitations of the leading framework, the multi-tier framework for measuring energy access (MTF) are discussed in detail and used in defining subsequent research questions explored in the empirical work. Broadly, this chapter provides the reader with an introduction to the status-quo of energy poverty and energy access measurement as relevant to countries in the Global South.

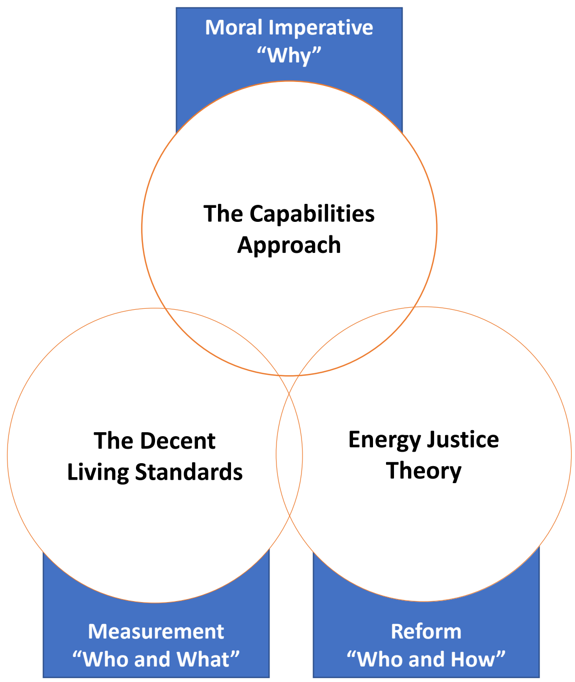

Figure 1: Graphical abstract of the theoretical foundation underpinning this research project.

The third chapter provides empirical evidence describing the relationships between electricity supply and use for the purposes of improving on contemporary multi-dimensional energy access measurement frameworks. It begins with an analysis of residential utilisation of electrical energy services and how this relates to distinct attributes of electricity supply in rural northern India. This is complemented by a similar analysis of productive utilisation of electrical energy services among micro- and small enterprises, also in rural northern India. The lessons from both of these pieces of research inform the final section, which describes multi-dimensional geographic and wealth-related energy access inequities in rural Nepal. The final section is unique in this work as it uses primary data from a household survey that I designed together with partner organisations across several rural municipalities in far-western and far-eastern Nepal.

The fourth chapter concludes by consolidating the argument for multi-dimensional energy access measurement both at the global and national levels. The first section presents an alternative multi-dimensional framework for measuring global progress towards SDG 7.1. This is compared against the current binary SDG 7.1 indicators and applied to recent nationally representative household survey data in 10 countries with energy infrastructure deficits. Following this cross-country comparison, the second section describes caste-disaggregated multi-dimensional energy supply trends following India's pro-poor energy policy reforms, highlighting the importance of multi-dimensional and disaggregated measurement to achieve more equitable outcomes.

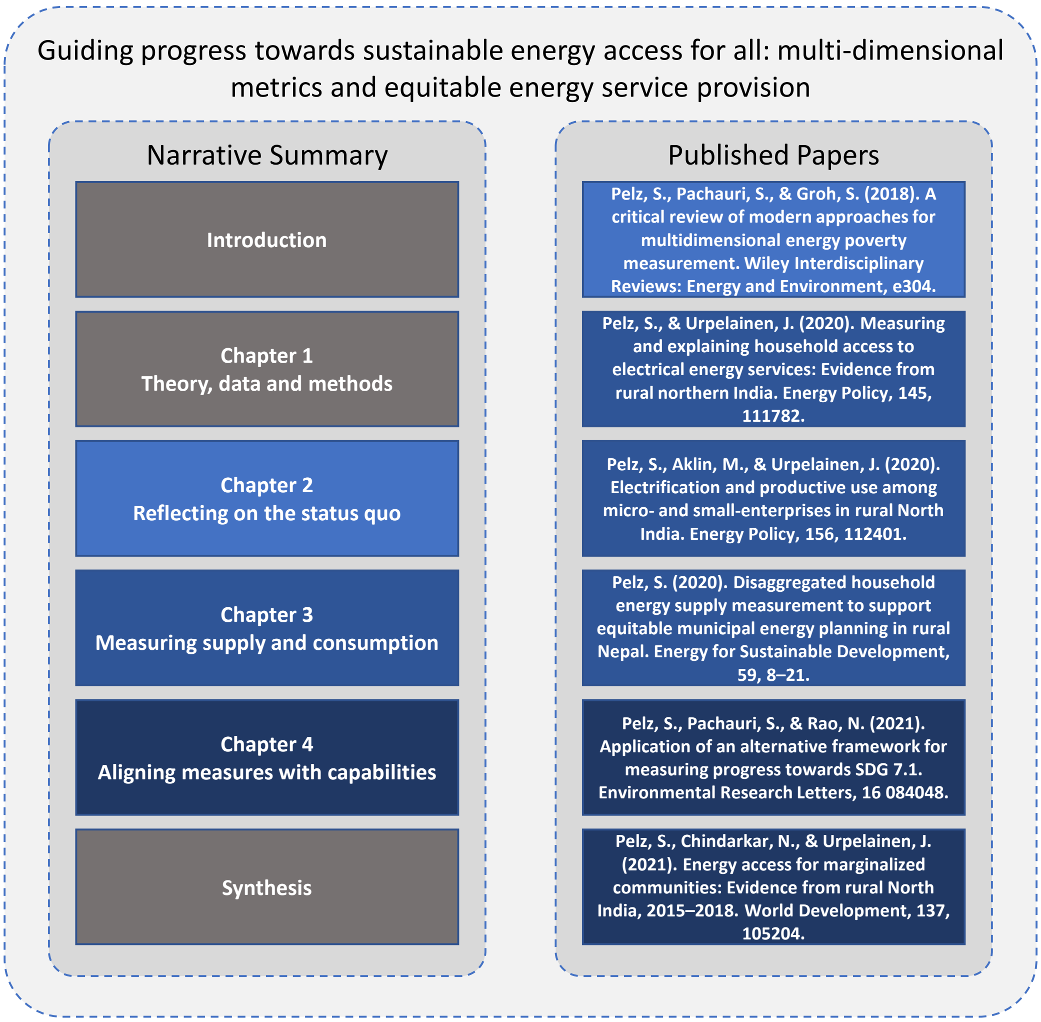

Figure 2: Graphical abstract of the research project.

In closing, a synthesis is provided, tying together the findings in the context of this narrative summary. This synthesis distils the key results from the preceding chapters and puts forward the main arguments that I seek to defend. A graphical abstract of the dissertation is provided in Figure 2.

Chapter 1

Theory, Data and Methods

1.1 Theoretical Foundation

Household access to energy can be assessed through a variety of lenses, leading to important and necessary philosophical debates about what is considered an adequate goal. For example, the goal of providing all households with a connection to the national grid is quite different from the goal of providing all households the ability to keep their homes at a comfortable temperature, adequately lit and free from smoke and other pollutants. The former is the dominant approach at both the national and global level and does not guarantee supply availability or affordable usage of the connection. The latter is largely restricted to the academic discourse and is considerably more complex and challenging to measure. This example effectively proxies the ongoing debate in energy access and energy poverty measurement in countries of the Global South[1]. A position taken here, either explicit or implicit, has intuitive flow-on effects on the design of national energy access policies and global energy access agenda setting. In this section, I describe my approach for exploring this debate through three contemporary theoretical approaches, which I collectively term *'justice-based'* approaches. Across all of these I maintain the premise that household energy access is desirable due to the livelihood and well-being improvements this unlocks, rather than the access alone. That is, however the measurement is conducted, the underlying motivation for providing all households with access to modern energy is the improvement this brings to their lives.

1.1.1 Capabilities Approach

I begin with the Capabilities Approach, a theoretical framework pioneered by Amartya Sen and Martha Nussbaum[2]. The Capabilities Approach is a normative

[1] I use the terminology of the 'Global South' for lack of a better alternative for describing poorer countries that remain in weaker positions as a result of historical and ongoing inequities in global resource and power distributions.

[2] For further reading, Robeyns & Byskov (2020) provide a concise history of the development of the Capabilities Approach. I draw my understanding of this approach mainly from three books, firstly, *The Idea of Justice* (Sen, 2010), secondly, *Creating capabilities: the human development*

framework that places the freedom of an individual to achieve well-being to the position of primary moral importance. Well-being, in turn, is defined as the capabilities to achieve a plurality of desired functionings. The terminology used here may appear somewhat cumbersome and indeed the interpretation has shifted over time. If we consider the need to keep oneself at a cool and comfortable temperature: physically being at a cool and comfortable temperature could be called a *functioning*, the practical ability to realise this through energy consumption or otherwise could be called a *capability*, and the ability to choose whether this is desired and act on this desire could be called a *freedom*. This is one of several possible interpretations of how freedoms, capabilities and functionings are interlinked, and should be seen as my interpretation for the purposes of this research project.

Both Sen and Nussbaum provide similar arguments for the moral value of a Capabilities Approach above other theoretical frameworks. Sen, it could be argued, speaks more to the comparative analysis enabled by the approach in terms of understanding differences in capabilities and freedoms, and stresses the importance of public deliberation in understanding which capabilities to consider. Nussbaum on the other hand, establishes ten *central capabilities* that are heterogeneous and irreducible, and speaks to the achievement of all of these for each individual from a theory of justice perspective. To help understand these differences, Robeyns proposes a separation between the Capabilities Approach as a framework and capabilities theories that result in its implementation, creating a modular structure to organise these (Robeyns & Byskov, 2020).

Robeyns' modular structure establishes a non-negotiable core that is the moral argument underlying both Nussbaum and Sen's contributions. It then adds subsequent optional modules that help structure divergent theoretical implementations. These optional modules include theoretical aspects such as the *purpose* and the *dimensions* captured, as well as practical aspects such as *empirical measurement* and *weighting*. Using this structure, one would consider Sen's writings to focus more on the overarching framework, while Nussbaum's work (not ignoring her immense contribution to the framework as a whole) would be considered a theoretical implementation. Robeyns' contribution thus provides a structure that is very helpful for those seeking to use the Capabilities Approach as a foundation in a specific context such as in aide of equitable energy access measurement and policy design.

Viewing the opening debate through a capabilities lens requires considering functionings, capabilities and freedoms individually in measuring progress towards sustainable energy access for all. This is considerably more complex than counting connections or aggregate consumption per capita as per the dominant approaches. Why would we need to move towards such complexity in energy access measurement? In *A Theory of Justice*, Sen describes four separate considerations that help communicate the importance of a capabilities lens in guiding progress towards a more egalitarian society. I use these considerations to reflect on energy access measurement, under the premise that access to energy is desirable for the well-being improvements this unlocks. The four considerations are paired with examples in the context of rural

approach (Nussbaum, 2011), and finally, *Wellbeing, Freedom and Social Justice* (Robeyns, 2017).

households in economically poorer countries in the Global South, the primary scope of my research.

- Firstly, are people with different individual characteristics, such as gender or wealth, equally able to derive the improvement to their well-being that access to modern energy provides? Here I consider a case where we were able to measure improvement to well-being in some imaginary uniform unit conditional on access to a modern energy source. Under these assumptions, does access to the modern energy source enable all people to achieve some minimum equivalent level of livelihood improvement, irrespective of differences in their individual characteristics?

- Secondly, does some minimum level of energy consumption necessary to achieve some standard level of (energy-related) well-being remain constant despite differences in the physical environment? Here I consider a case where we can assume that all people have equivalent characteristics and abilities to transform energy into well-being improvements. Under these assumptions, are all people's abilities to convert some minimum level of energy consumption into desired well-being improvements exogenous to differences in climatic conditions?

- Thirdly, is the ability of people to convert a connection to a modern energy source into well-being improvements exogenous to differences in the social climate? Here I consider a case where we assume uniform characteristics and physical environments. Do social constructs, such as tribe or caste, modify the ability of some sub-population to convert access, measured as a connection to a modern energy source, into well-being improvements equivalent to that of the majority?

- Fourthly, do relational perspectives, such as the societal expectations in richer and poorer national contexts influence the relative well-being improvements able to be derived from some minimum level of energy consumption? Here I consider the case where two individuals have identical levels of energy consumption but live in two different societies with vastly different levels of wealth. Is this minimum level of energy consumption able to provide equivalent improvements to relative well-being for these two individuals?

The considerations described here, while somewhat rhetorical in nature, throw into question whether the dominant connection-based approaches in guiding progress towards improved energy access for all can achieve equitable outcomes across an entire population. Indeed if the goal is to ensure sustainable energy for all for the purposes of improving well-being, it would appear that we must look beyond connections or consumption aggregates towards multi-dimensional measures that capture utilisation and resulting capabilities.

While I draw directly from Sen's writings in the *The Idea of Justice* (Sen, 2010) in formulating these considerations in the context of energy access, my work follows that of other scholars, most notably Day, Walker, & Simcock (2016), who were among the first to formally make this link in their discussion of energy poverty as a deprivation in capabilities. They define energy poverty using the framework of the Capabilities Approach as follows:

"an inability to realise essential capabilities as a direct or indirect result of insufficient access to affordable, reliable and safe energy services, and taking into account available reasonable alternative means of realising these capabilities" (Day, Walker, & Simcock, 2016).

I consider the work of Day, Walker, & Simcock (2016) a pioneering theoretical implementation of the Capabilities Approach in the context of energy poverty using both core and optional modules as described by Robeyns. While not yet complete in terms of measurement or empirical applicability, their implementation provides an overarching definition that neatly encapsulates each of the four considerations described above. This definition is thus one component of the theoretical foundation underpinning this dissertation. It informs the moral motivation for looking beyond connection-based measures and embracing complexity in describing energy poverty.

1.1.2 Decent Living Standards

The Decent Living Standards propose a framework for assessing the minimum material requirements necessary to meet basic human entitlements for decent living (Rao & Min, 2018). This draws from both the basic needs approach as well as the Capabilities Approach, the latter having being discussed in detail in the previous sub-section. The basic needs approach referred to here is described within *A Theory of Human Needs* (Doyal & Gough, 1984) and should not be confused with Maslow's hierarchy of needs[3]. The basic needs approach stands somewhat as an alternative to the theory of justice described by Nussbaum as well as the Capabilities Approach more broadly, while pursuing the common agenda of defending universal human interests[4]. Taking a hierarchical approach, it begins with a stipulation of normative, moral universal goals. These are comparable to the motivation underlying the Capabilities Approach, and are defined as the avoidance of serious harm, social inclusion and participation in decision making processes.

Moving from these universal goals, the basic needs approach defines a set of basic needs under the broad categories of health and autonomy. These find similarities in Nussbaum's theoretical implementation but diverge from the original Capabilities Approach in terms of stipulating heterogeneous and non-replaceable minimums. Basic needs include such aspects as physical health and survival, cultural understanding, opportunity and critical autonomy. Finally, the notion of 'satisfiers' is defined. 'satisfiers' are *objects, activities and relationships that satisfy our basic needs* (Doyal & Gough, 1984). While 'satisfiers' may depend on cultural and other contextual differences, they can be broadly captured under so-called 'universal satisfier characteristics'

[3] Maslow's hierarchy of needs is a concept in psychology that seeks to define human needs or motivations as a hierarchical concept. This is not relevant to this work and thus further explanation is not pursued beyond distinguishing this from the basic needs approach of Doyal & Gough (1984)

[4] For further reading, Gough (2014) provides a helpful comparison and critique of both theories

or 'intermediate needs' which outline the characteristics of satisfiers necessary to satisfy our basic needs.

The Decent Living Standards establish a universal set of basic material requirements that correspond to the intermediate needs defined under the basic needs approach as well as the overarching goals of the Capabilities Approach. As such, the Decent Living Standards are a prerequisite, but not sufficient, to achieve multi-dimensional human well-being for *everyone*. The Decent Living Standards consist of the following constituents:

"Nutrition, Shelter, Living conditions, Clothing, Health care, Air quality, Education, Communication, Information access, Mobility and Freedom to gather/dissent" (Rao & Min, 2018).

The definition of material requirements to satisfy these constituents are guided by three principles. The first principle states that a material prerequisite must be *necessary and indispensable, or globally desired* (Rao & Min, 2018). That is, if there are multiple material satisfiers to some need, that which is globally desired is selected, otherwise if there is only one necessary and indispensable requirement, it is included. The second principle states that the prerequisite must limit the risk of harm to achieving basic human well-being to an acceptable threshold. The risk or acceptable threshold here is defined in terms of both the extent of harm and the likelihood of this occurring. Two boundary conditions are set, such that freedom from 'extreme discomfort' within the home is seen as freedom from both *prolonged* exposure to some harm (e.g. indoor air pollution), as well as *excessive* exposure to some harm (e.g. manual drudgery). The third principle recognizes that basic human entitlements *give rise to material requirements at the household, community or societal level* (Rao & Min, 2018). That is, we must also look beyond the household and consider the need for community and societal level material requirements necessary for individual well-being.

These principles translate into minimum material requirements at the household and collective levels under each constituent of the Decent Living Standards as shown in Figure 1.1. Each of the minimum material requirements are thus so defined as to be globally applicable, specific and measurable. This is an important level of specificity as it enables a formulation of energy related requirements for a decent living standard. Notably, one that also satisfies the definition of energy poverty through a capabilities lens. The Decent Living Standards thus form another component of the theoretical foundation underpinning this research project. They create a bridge from the moral motivation of embracing complexity in energy poverty measurement to its practical implementation and thus inform the empirical analysis throughout the work.

Dimension	Household requirements	Collective Requirements	Energy Related
Physical well-being			
Nutrition			
Food	Total calories, protein, micro-nutrients		
Cold storage	Fridge (or other technology)		←
Shelter			
	Solid walls and roof		
Living conditions			
Sufficient, safe space	Min. floor space	Electricity, water and sanitation infrastructure	←
Basic comfort (bounded temperature/humidity)	Modern heating/cooling equipment		←
Hygiene	In-house imp. toilets. Min., accessible water supply		
Clothing			
	Min. clothing materials	Washing machines per 1000 persons	←
Health care			
Accessible and adequate health care facilities		Min. health exp. per cap. Min. physicians per '000 people	
Air quality			
Maximum ambient particulate matter (PM2.5)	Clean cook stoves	Restricted transport infrastructure	←
Social well-being			
Education			
	Nine years schooling	Equipped schools. Teachers per 1000 persons	
Communication			
	Phone (1 per adult)	ICT infrastructure	←
Information access			
	Television/internet device		←
Mobility			
	Access to public transport, or vehicle, if essential	Public transport and road infrastructure	
Freedom to gather/dissent			
		Public space, sq. m. per 1000 persons	

Figure 1.1: Material requirements of the decent living standards, adapted from: Rao & Min (2018)

1.1.3 Energy Justice

Energy Justice as a body of literature deals with all manner of human-system relationships in the context of energy production and its use. As a concept, it also draws from the Rawlsian tradition (Rawls, 1971) and other philosophical contributions toward a modern theory of justice. Energy Justice literature provides the language necessary for understanding that energy and it's upstream and downstream costs and benefits are strongly linked with each of our lives and society as a whole. With this framing, the shared costs and benefits across different groups and indeed across time are able to be considered and weighed. Intuitively, this concept shares its roots with the Capabilities Approach and the basic needs approach underlying the Decent Living Standards.

Sovacool (2014) and Jenkins, McCauley, Heffron, Stephan, & Rehner (2016) synthesise the formative literature in this emerging field. Among the 14 avenues of research derived out of a thorough review of energy literature, Sovacool (2014) puts forward the argument for further work in the fields of philosophy and ethics in energy research. He highlights this research gap in the literature and posits that

"(notions) of justice can emphasise how energy serves as a material prerequisite for many basic goods to which people are entitled" (ibid.).

This is expanded more broadly to discussions of a just and fair society and distributive benefits and burdens of modern energy systems. This synthesis of literature gives rise to several research questions that engage with these broader themes without yet formulating a theoretical approach grounded in justice theory. Such questions include *"How does a particular mode of thought or technology foster the wellbeing of future generations? (17)"* and *"How should the costs and benefits of energy production and use be distributed? (18)"* (ibid.). The notion of justice and fairness he discusses are thus not restricted to comparisons across segments of society or across national borders, but also consider injustices across time.

Table 1.1: The normative and evaluative aspects of energy justice, source: Jenkins, McCauley, Heffron, Stephan, & Rehner (2016)

Tenets	Evaluative	Normative
Distributional	Where are the injustices?	How should we solve them?
Recognition	Who is ignored?	How should we recognise?
Procedural	Is there fair process?	Which new processes?

Jenkins, McCauley, Heffron, Stephan, & Rehner (2016) provide structure to this research avenue, summarising and generalising the three tenets of Energy Justice that can be found in the formative literature. These are the tenets of *distributional*, *recognition* and *procedural* justice. These tenets have been developed with the intention to evaluate: *"(a) where injustices emerge, (b) which affected sections of society are ignored, (and) (c) which processes exist for their remediation in order to (i) reveal, and (ii) reduce such injustices"* (ibid.). As indicated in the final phrase in this definition, these tenets are intended to be applied in both an evaluative and normative manner. That is, researchers and practitioners can use these tenets to both describe the extent to which injustices may occur and also develop solutions to these injustices along the framing of each tenet. Table 1.1 provides a summary of the three tenets and their evaluative and normative functions.

Distributional justice *"recognises both the physically unequal allocation of environmental benefits and ills, and the uneven distribution of their associated responsibilities"* (ibid.). As an example, one could consider distributional justice in the placement of electricity and clean cooking fuel distribution and transmission infrastructure. Where are these supply gaps, and how should we solve them? Importantly, the *where* does not only refer to the spatial inequities but also across segments of the population. That is, while the role of geography and corresponding infrastructure costs in sparsely populated remote areas are evidently a driver of the energy access deficit, we cannot forget historical socio-political structures that guided the development of existing energy systems in many countries. The lock-in effects and challenges created by colonial energy systems continue to influence energy policy today (Straeten & Hasenöhrl, 2016).

Recognition justice *"states that individuals must be fairly represented, that they must be free from physical threats and that they must be offered complete and equal political rights"* (ibid.). These injustices are seperated into those resulting from *non-recognition* and *misrecognition*. As an example of the former, the in-home temperature bounds that define fuel poverty in the UK were only recently modified to reflect the specific needs of the old and the infirm (Walker & Day, 2012). As an example for the latter, the misrepresentation of rural women in emerging economies as actors with little agency, as passive victims of energy poverty or as uniquely empowered by energy access has drawn criticism from within feminist development scholarship (Listo, 2018).

Procedural justice *"manifests as a call for equitable procedures that engage all stakeholders in a non-discriminatory way"* (ibid.). Special emphasis is placed on the normative aspect of Energy Justice here, as incumbent procedures and processes undoubtedly influence injustices identified by the other tenets. Along the normative aspect of this tenet, three specific mechanisms of inclusion are defined as *"local knowledge mobilization, greater information disclosure, and better institutional representation"* (ibid.). As an example, the decentralisation of energy access planning governance in Kenya intended to improve on all three of these mechanisms but remained hamstrung by an unwillingness of the central government to fully relinquish their power, to the detriment of energy access progress in the country's rural areas (Sieff, 2020).

Alignment of the three tenets of Energy Justice with the capabilities and basic needs approaches is evident in these formulations. They function in parallel and provide structure in terms of moving from the evaluative assessment towards solutions. Both the evaluative and normative aspects of the three tenets thus comprise the final part of the theoretical foundation underpinning this work.

1.2 Data and methods

The primary contribution of this research project is in the application of established quantitative analysis methods and normative theoretical 'justice-based' approaches to explore equitable energy access measurement and policy outcomes. Six peer-reviewed papers form the body of the work. The empirical methods are grounded largely in econometric analysis (including complex survey design and analysis) and include some geospatial analysis. This is applied on both primary and secondary survey data as well as remotely sensed spatial datasets. The analysis is descriptive in nature. Causal statements are not made, as causal relationships are not identified. The contribution is thus one of generating evidence of possible correlations and describing differences across groups and over time. Table 1.2 lists the peer-reviewed papers and the datasets investigated.

Table 1.2: An overview of the six peer-reviewed papers and their corresponding datasets.

ID	Title	Data
1	Pelz, S., Pachauri, S., & Groh, S. (2018). A critical review of modern approaches for multidimensional energy poverty measurement. Wiley Interdisciplinary Reviews: Energy and Environment, e304. `doi:10.1002/wene.304`	Selected publications
2	Pelz, S., & Urpelainen, J. (2020). Measuring and explaining household access to electrical energy services: Evidence from rural northern India. Energy Policy, 145, 111782. `doi:10.1016/j.enpol.2020.111782`	ACCESS `doi:10.7910/DVN/AHFINM`
3	Pelz, S., Aklin, M., & Urpelainen, J. (2020). Electrification and productive use among micro- and small-enterprises in rural North India. Energy Policy, 156, 112401. `doi:10.1016/j.enpol.2021.112401`	REDI `doi:10.7910/DVN/1ZNLUY`
4	Pelz, S. (2020). Disaggregated household energy supply measurement to support equitable municipal energy planning in rural Nepal. Energy for Sustainable Development, 59, 8–21. `doi:10.1016/j.esd.2020.08.010`	Primary survey data, secondary spatial data
5	Pelz, S., Pachauri, S., & Rao, N. (2021). Application of an alternative framework for measuring progress towards SDG 7.1. Environ. Res. Lett. 16 084048. `doi:10.1088/1748-9326/ac16a1`	MTF `doi:energydata.info`
6	Pelz, S., Chindarkar, N., & Urpelainen, J. (2021). Energy access for marginalized communities: Evidence from rural North India, 2015–2018. World Development, 137, 105204. `doi:10.1016/j.worlddev.2020.105204`	ACCESS `doi:10.7910/DVN/AHFINM`

1.2.1 Overview of datasets

The primary and secondary datasets analysed across the six peer-reviewed papers are briefly described here. Further descriptive analysis and summary statistics are provided in the subsequent chapters as well as the papers themselves. Replication archives and original datasets are provided for all empirical papers as far as this was possible.

Literature

Paper 1 analyses a set of selected publications that discuss contemporary energy poverty measurement literature and measurement approaches. These include both peer-reviewed publications and grey literature describing advances in energy poverty measurement driven by non-academic organisations.

ACCESS

Paper 2 & 6 use the ACCESS dataset, which was produced by the Council for Energy, Environment and Water, the National University of Singapore and the Initiative for Sustainable Energy Policy at Johns Hopkins University. ACCESS is a representative panel survey dataset of households in rural areas of the six states with the highest electricity access deficit in India. The surveys were conducted in two waves, in 2014–15 (N = 8563 in 714 villages) and 2018 (N = 9072 in 756 villages). Further detail of the sampling strategy, data collection approach and limitations can be found on the harvard dataverse using the following permanent identifier: `https://doi.org/10.7910/DVN/AHFINM`. A replication archive for Paper 2 is available here: `https://doi.org/10.7910/DVN/JXPOYF`. A replication archive for Paper 6 is available here: `https://doi.org/10.7910/DVN/YNDP93`.

REDI

Paper 3 uses the REDI dataset, which was produced by Smart Power India (an initative of the Rockefeller foundation) and the Initiative for Sustainable Energy Policy at Johns Hopkins University. REDI is a cross-sectional survey dataset of 2,004 small- and micro enterprises from similar rural villages in Bihar, Uttar Pradesh, Rajasthan and Odisha. Further detail of the sampling strategy, data collection approach and limitations can be found on the harvard dataverse using the following permanent identifier: `https://doi.org/10.7910/DVN/1ZNLUY`. A replication archive is available here: `https://doi.org/10.7910/DVN/YAGQ6P`.

Nepal Survey

Paper 4 relies on primary household survey data from rural Nepal, as well as publicly available spatial datasets describing population, night-time lights and electricity infrastructure. The primary data collection was funded by the GIZ Nepal RERA program, where two Master students from Europa-Universität Flensburg, Binita Shrestha and Niraj Shrestha were conducting an internship. This involved the design and application of a self-weighted sampling strategy that is discussed in detail in Paper 4 itself. A replication archive is unfortunately not publicly available as the survey data gathered was not able to be made publicly available. This can be provided upon request and following consent provided by GIZ Nepal.

MTF ESMAP

Paper 5 uses nationally representative survey data from 10 countries countries gathered under the World Bank's Energy Sector Management Assistance Program (ESMAP) Multi-tier Framework for Measuring Energy Access (MTF) surveys. As of writing, nationally representative survey data is available for Rwanda, Ethiopia, Cambodia, Myanmar, Honduras, Nepal, Kenya, Niger, Sao Tome and Principe and Zambia. Further detail of the sampling strategy, data collection approach and limitations can be found at `https://energydata.info`. A replication archive is available here: `https://doi.org/10.7910/DVN/DP2V5I`.

1.2.2 Overview of methods

Finally, the methods applied across all six peer-reviewed papers are briefly summarised here. As this is a cumulative publication-based dissertation, this is purposely left quite sparse as detailed methods and model specifications are left to the papers and their appendices. Nevertheless, the basic approach is described here and notable assumptions and limitations of the methods applied are discussed in the subsequent chapters following their use. The intention is to provide a brief overview of the methods here, followed by a more intuitive discussion of the methods and limitations in the context of their application in the subsequent chapters, and finally detailed methods, assumptions and limitations in the papers themselves. Figure 1.2 describes the overarching methodological framework, which links the applied methods and describes the design of the research.

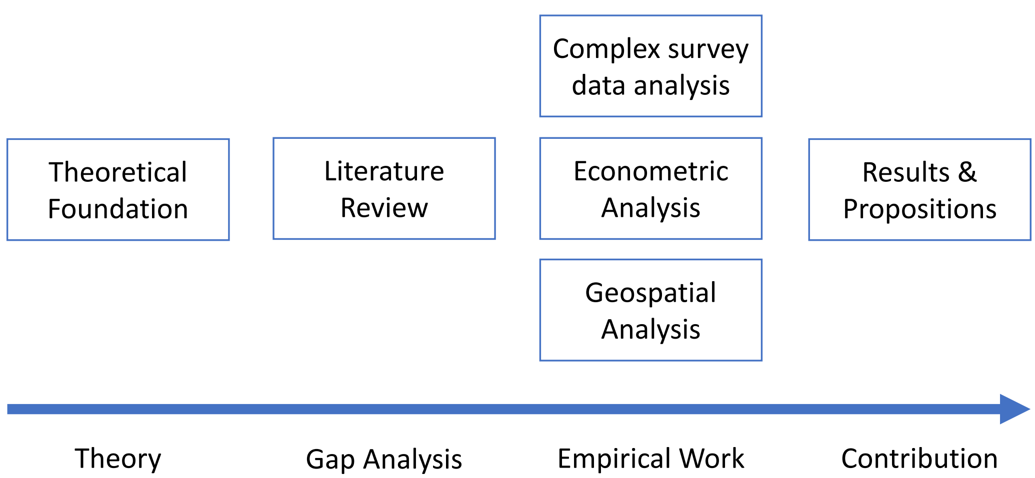

Figure 1.2: Graphical abstract of the methodological framework.

Literature review

The work begins with a narrative literature review conducted in Paper 1. Narrative reviews are appropriate for a more in-depth qualitative analysis of specific articles at the cost of the scientific rigour necessary for good quality meta-analysis of the state-of-art (see Sovacool, Axsen, & Sorrell (2018) for a robust discussion of narrative literature reviews). This is an acceptable trade-off for this paper as our intention is to speak specifically to the recent progress in leading energy access measurement approaches which necessitates biased literature inclusion and exclusion criteria.

Complex survey data analysis

Across Papers 2-6, descriptive analysis of complex survey data is applied. This involves calculating both weighted and un-weighted aggregates of selected variables, as well as observing the distributions of these variables across the sampled population. Various approaches are used including summary statistics tables, balance tables, distribution visualisations such as density plots, correlation plots and other descriptive approaches to present summarised data in a digestible format. As necessary, sampling design weights that increase or reduce the weight of an observation to reflect the actual proportions in the overall population are used. The motivation for the targeted use of survey design weights is as follows: aggregates from a dataset generated through clustered sampling of n units from primary sampling units such as villages need to be corrected for the proportion of the population living in each village with respect to the entire population, if the intention is to say something about the population as a whole. Alan S. Gerber (2012) was the primary reference for this analysis of complex survey data. In the special case of Paper 4, survey design weights are not needed for a representative descriptive analysis as the sample is self-weighted by design. More detail on the representative sample design used in Paper 4 can be found in its appendices, included at the end of the narrative summary.

Econometric analysis

Across Papers 2-6, the goal of the econometric analysis is to test for and establish plausible relationships between variables of interest. Modern econometrics describes the ideal scenario as having both a good understanding of the data generating process and a randomised experiment enabling an apples-to-apples comparison of two groups. The data generating process is the theory describing how the independent variables (the *treatment* and other covariates) are related to the dependent variable (the change in which describes the *effect*). Ideally, all that varies is the treatment, while the other relevant covariates across both groups are effectively identical. This enables the *identification* of the effect as being caused by the variation in treatment. Randomised experiments are often not possible for a variety of reasons. Instead, the ideal scenario above is replaced with a quasi-experimental approach that uses observational data and a set of analytical approaches to approximate as far as possible a randomised experiment. The second scenario describes the work conducted here.

The analytical approaches employed across Papers 2-6 can be summarised as variations of multiple linear regression with fixed-effects. Causal statements are not made as the available data and analytical approaches do not allow this interpretation. Formally, identification is not achieved, although plausible descriptive relationships against the backdrop of this limited identification are discussed. These approaches rely on the standard Gauss-Markov assumptions for applying simple or multiple linear regression models to real-world data and more recent developments in applied econometrics. The five assumptions (LR1-LR5) for conducting ordinary least squares (OLS) estimation of a linear regression model are described by in Table 1.3 below]. A detailed discussion of the mechanics of multiple linear regression is foregone here as this is beyond the scope of a narrative summary and model specifications are provided in the papers themselves. The following books were the primary references for this work: Wooldridge (2013), Angrist (2009), Cunningham (2021) and Klein (2021).

Table 1.3: Gauss-Markov assumptions for ordinary least squares (OLS) estimation of linear regression models, source: Wooldridge (2013).

Assumption	Description
LR1, Linearity	a linear relationship is assumed between the dependent and independent variables
LR2, Random Sampling	the model is applied to a random sample from the population
LR3, Variation	the dependent variable is not the same value across the independent variable range
LR4, Zero Conditional Mean	the model residuals are not correlated with fitted value of the model
LR5, Homoskedasticity	the model residuals have the same variance across the independent variable range

Linear regression analysis with fixed-effects is essentially the introduction of group-level dummy variables to a linear regression model. These group-level dummy variables capture all (unwanted) time-invariant heterogeneity across groups. This specifically restricts the comparison to ‘within’ the groups defined by the group-level dummy variables used, as long as the unwanted differences across the groups are time-invariant. In selected work (Papers 2 and 6) the linear regression analysis is extended to the analysis of panel data, which is the analysis of identical units over two or more periods in time. Panel data is typically exploited to adjust for unobserved confounding by including dummy variables for group and time. This is then called ‘two-way fixed effects’ (TWFE), where the intention is to eliminate unwanted variation across groups and across time such that we are left with the variation of interest - that which relates to, and only to, our specified treatment and dependent variables. There are *severe* problems with this assumption specifically with respect to deriving a robust causal estimate due to potential unequal variation in treatment across groups over time (see for example Chaisemartin & D’Haultfœuille (2020)). The applications in this work make no attempt at such causal estimation and thus avoid leaning heavily on such assumptions, however the work remains vulnerable to valid criticism from the emerging literature on TWFE model estimation. Finally, it is important to note that given the complex clustered survey data analysed, corrections for heteroskedacity and correlation of standard errors within sample clusters are applied using cluster-robust standard errors throughout this work.

Geospatial analysis

Geospatial analysis is limited to Paper 4 and relies on two different unsupervised machine learning (ML) methods to interpolate complex clustered survey data across geographic population clusters. This is done in order to generate data describing electricity supply in villages within survey administrative boundaries but without any survey observations due to the efficient clustered sampling design. The first ML method is the clustering algorithm used to distinguish geographic population clusters (also called settlements, or villages in rural areas) from the remotely sensed population datasets. Here the *DBSCAN* clustering algorithm is applied, which clusters spatial data by categorising individual datapoints into core, border or noise categories based on the number of points (minPts) within a given radius (r) around each point. DBSCAN is preferable to other clustering options such as k-means as unlike others it does not impose an assumption on the shape of the relationship between X and Y. This lends itself to population clustering as the settlement can form arbitrary shapes such as curved lines depending on the local geography and cultural context. A discussion of the DBSCAN algorithm, its merits, limitations and implementation in the R statistical programming language is provided by Hahsler, Piekenbrock, & Doran (2019). The second ML method is a predictive algorithm known as boosted regression trees (BRT), available in the Caret package for the R statistical programming language (Kuhn, 2008). The BRT algorithm creates sequential models or trees which are improved with each iteration and combined in order to provide an ensemble prediction. Here, BRT is used to model grid and minigrid connection likelihoods across each rural municipality by linking the geo-coded household survey dataset with several spatial datasets available for all of Nepal. A detailed justification and discussion of these methods are left to Paper 4 and its appendices.

R statistical programming language

All of the empirical work was conducted using the R statistical software language (R Core Team, 2021) in the R Studio IDE (RStudio Team, 2020). Data processing was done using the tidyverse (Wickham et al., 2019) and associated packages. The *here* package was used to enable replication code to be more easily executed on any operating system (Müller, 2020). The applied econometric work is primarily conducted using the *fixest* package (Bergé, 2018). This narrative summary was prepared using R Markdown with the Thesisdown template (Xie, Dervieux, & Riederer, 2020). All other packages used are cited in the replication archives and the papers themselves. Omissions are not intentional and will be immediately corrected if any are reported.

Chapter 2

Reflecting on the Status Quo

2.1 Energy Services

What is an energy service? An entire article was written to gather a common understanding of this phrase from within the recent energy policy and social sciences literature. This resulted in the following definition:

"Energy services are those functions performed using energy which are means to obtain or facilitate desired end services or states" (Fell, 2017).

Following this definition, *space cooling* or *lighting* would be considered an energy service but the physical electricity connection and supply would not. This is an important distinction to draw in the reader's mind. Outside of the academic discourse, the notion of a service the household receives is typically considered at the level of the utility - such as the water service or telecommunications service, and reflects the quality of the supply or connection. This is not the case here. Throughout this work, and indeed in most of the literature discussing energy access, the definition of energy services as *functions performed using energy* prevails. A summary of household energy services from the seminal literature on this topic is provided in Table 2.1 below.

Table 2.1: Historical household energy service definitions, source: Pelz, Pachauri, & Groh (2018).

Year	Source	Definition
1985	Goldemberg, Johansson, Reddy, & Williams (1985)	Cooking, lighting, television, refrigeration, hot water, and clothes washer
2005	UNDP (2005)	Cooking, lighting, communications, water heating, refrigeration, water pumping, and transport
2005	UN Energy (2005)	Cooking, lighting, telecommunications, heating, motive power, mechanical power, and transport

Year	Source	Definition
2006	Modi, McDade, Lallement, & Saghir (2006)	Cooking, illumination and Information & Communication Technologies (ICT), appliances for household and commercial activities, and mechanical power
2012	Practical Action (2012)	Cooking and water heating, lighting, information and communications, space heating and cooling
2012	Nussbaumer, Bazilian, & Modi (2012)	Cooking, lighting, services provided by means of household appliances, communication and entertainment
2015	Bhatia & Angelou (2015)	Cooking, lighting, entertainment and communications, space cooling and heating, refrigeration, mechanical loads, and product heating

These lists are united in their recognition that energy is necessary for multiple different end-uses within and around the home. They reinforce our understanding that our lived experience with energy is reflected in the services we use this for, rather than the kilowatt-hours consumed. This definition of energy services as *functions performed using energy* aligns with definition of energy poverty under the Capabilities Approach, as discussed in Chapter 1. With this understanding of energy services we can directly measure energy poverty as the deficit in specific energy-related functions (or *functionings* in the Capabilities language).

Achieving access to a set of energy services is naturally a function of the supply provided. While the focus in the literature in terms of development outcomes has been on energy services, and indeed the definition of energy poverty is more explicit about this aspect, supply must be of a sufficient reliability, quality and affordability to unlock these. This is an important consideration as it underlines that approaching energy poverty from a Capabilities perspective is not restricted to abstract notions of fairness. Rather, these can be used as a foundation for establishing specific and measurable multi-dimensional supply targets useful for policy development and general goal setting. The shift in perspective here is that we must start with a definition of those energy services necessary for human well-being, and move from this towards the supply necessary to enable their utilisation. The differences across the lists above shed light on a slowly converging understanding of what we may call a *basic* or *minimum* set of energy services necessary for human well-being.

2.2 Measurement Frameworks

Although it is widely understood that connection to a modern energy source is a prerequisite but not sufficient to enable household access to multiple different functions (end-uses), measurement of household energy access for global agenda setting as well as national energy policies remains a binary affair. Advances in multi-dimensional measures provide precedent and guidance on transitioning towards indicators better aligned with the overarching goal of energy services as prerequisites for human well-being. I will begin with a brief summary of the dominant measures, before moving on to the recent development of multi-dimensional measurement frameworks.

The sustainable development goals (SDGs) reflect the current peak multi-lateral goals for human development, taking over from the Millennium Development Goals, which failed to include energy (UN, 2015). The SDG for energy access (SDG7.1) is rich in its wording, setting a target for 2030 to *"ensure universal access to affordable, reliable and modern energy services."* (UN, 2015). Reflecting on this target from a justice-based approach as discussed in Chapter 1, and using the definition of energy services discussed above, one would be reasonably optimistic of its ambition to achieve a more egalitarian society where all are ensured access to the necessary energy services for a decent life. The indicators to measure progress towards this goal, however, capture only the connection to a modern energy source, as shown below.

- Indicator 7.1.1: Proportion of population with access to electricity
- Indicator 7.1.2: Proportion of population with primary reliance on clean fuels and technology

These indicators are far less ambitious than the overarching goal and are unlikely to capture an adequate depth of energy poverty with respect to access to energy services. They contain no explicit targets for affordability, reliability or indeed which energy services are considered necessary for human well-being. This is a canonical example for the contemporary translation of energy access as a prerequisite of human well-being to the measures used to capture progress towards this. Most national-level energy access goals in low and middle income countries rely on similar or identical targets.

2.2.1 Multi-dimensional Energy Poverty Index (MEPI)

The MEPI aligns closely with the Capabilities Approach and the other justice-based approaches, focusing on evaluating deprivation of basic household energy services. As shown in Table 2.1, the MEPI describes *basic* energy services as, *"cooking, lighting, services provided by means of household appliances, communication and entertainment"* (Nussbaumer, Bazilian, & Modi, 2012). The indicators for measuring access to these basic energy services are shown in Table 2.2.

The MEPI was designed with a view as to the availability of data necessary in its practical implementation. Here, the Demographic and Health Survey (DHS) survey data was selected as the most widely gathered dataset with sufficient granularity with respect to energy services. Nevertheless, the lack of detailed data within the DHS constrains the MEPI to measure only specific appliance ownership and physical access to energy carriers. It does not contain indicators for affordability or reliability of supply.

Table 2.2: The multi-dimensional energy poverty index (MEPI), source: Nussbaumer, Bazilian, & Modi (2012).

Energy service	Proxy measure of deprivation	Weight
Cooking	Usage of any fuel beside electricity, LPG, kerosene, natural gas, or biogas	0.2
Cooking	Food cooked on stove or open fire (no hood/chimney) if using any fuel beside electricity, LPG, natural gas, or biogas	0.2
Lighting	No access to electricity	0.2
Services from appliances	No fridge	0.13
Entertainment / education	No radio or television	0.13
Communication	No phone land line OR a mobile	0.13

As indicated by the weight column, the MEPI weights deprivation of each individual dimension in terms of subjective relative importance. The intention is to reduce access to distinct energy services into a single score from 0-1, with 0 indicating decent access to energy services and 1 indicating complete deprivation. This transformation is practical for simplifying comparisons across energy services, but is not based on any empirical evidence or theory. The authors note, in fact, that these weights need to be evaluated for a given national context (Nussbaumer, Bazilian, & Modi, 2012). A method for adjusting this weighting based on nationally representative variables been yet to be defined, and in practice the nominal weights remain in common usage. Following aggregation using the defined weights, a multidimensional energy poverty cut-off value is defined at 0.3, implying that “a person is considered as energy poor if, for instance, she has no access to clean cooking or does not benefit from energy services supplied by electricity” (Nussbaumer, Bazilian, & Modi, 2012).

2.2.2 Total Energy Access (TEA)

The Total Energy Access framework (TEA) developed by Practical Action broke new ground in its definition of minimum targets for both access to basic energy services and electricity supply (Practical Action, 2010, 2012). The ‘Minimum standards for household energy access’ (MSHEA) of the TEA goes further than the MEPI, describing detailed requirements for achieving decent access to selected energy services, aligning even more closely with the justice-based approached discussed in Chapter 1. This is shown in Table 2.3. None of the selected energy services is given precedence, and unlike the MEPI, no explicit aggregation is proposed. Rather, each individual energy service is considered separately and equally, with the intention to be displayed as a dashboard rather than a single score. While the standards described here align much closer with the theoretical improvements to well-being that modern energy services provide, application of this framework has not been seen outside of the publications produced by Practical Action. The framework has likely seen low uptake due to data limitations and the need for bespoke, complex and thus costly household surveys.

Table 2.3: The TEA framework - minimum standards for household energy access, source: Practical Action (2012).

Energy service	ID	Minimum standard
Lighting	1.1	300 lm for a minimum of 4 hours per night at household level
Cooking and water heating	2.1	1 kg woodfuel or 0.3 kg charcoal or 0.04 kg LPG or 0.2 litres of kerosene biofuel per person per day, taking less than 30 minutes per household per day to obtain
	2.2	Minimum efficiency of improved solid fuel stoves to be 40% greater than a three-stone fire in terms of fuel use
	2.3	Annual mean concentrations of particulate matter (PM2.5) < 10 µg/m3 in households, with interim goals of 15 µg/m3, 25 µg/m3 and 35 µg/m
Space heating	3.1	Minimum daytime indoor air temperature of 18°C
Cooling	4.1	Households can extend life of perishable products by a minimum of 50% over that allowed by ambient storage
	4.2	Maximum apparent indoor air temperature of 30°C
Information and communications	5.1	People can communicate electronic information from their household
	5.2	People can access electronic media relevant to their lives and livelihoods in their household

Unlike the quantitative and quite detailed nature of the MSHEA, the corresponding Energy Supply Index (ESI) of the TEA describes ordinal quality levels on a largely qualitative basis. The ESI is split across household fuels (referring to cooking) and electricity access, both having 6 quality levels (0-5). This is shown in Table 2.4. While individual dimensions of quality and reliability are mentioned within the framework, they are not explicitly defined. This lack of clarity in the definition of chosen dimensions within the ESI hampers meaningful comparison of energy supply over time and across countries. The ordinal nature of the framework is not based on empirical evidence or theory and favours an AC grid connection without reasonable justification as to how this relates to the selected energy services described within the MSHEA.

Table 2.4: The TEA framework - the energy supply index, source: Practical Action (2012)

Energy supply	Level	Quality of supply
Household fuels	0	Using non-standard solid fuels such as plastics
	1	Using solid fuel in an open/three-stone fire
	2	Using solid fuel in an improved stove

Energy supply	Level	Quality of supply
	3	Using solid fuel in an improved stove with smoke extraction/chimney
	4	Mainly using a liquid or gas fuel or electricity, and associated stove
	5	Using only a liquid or gas fuel or electricity, and associated stove
Electricity	0	No access to electricity at all
	1	Access to third party battery charging only
	2	Access to stand-alone electrical appliance (e.g. solar lantern, solar phone charger)
	3	Own limited power access for multiple home applications (e.g. solar home systems or power-limited off-grid)
	4	Poor quality and/or intermittent AC connection
	5	Reliable AC connection available for all uses

2.2.3 Multi-tier Framework for Measuring Energy Access (MTF)

The Multi-Tier Framework for Measuring Energy Access (MTF) follows the TEA in aligning multi-dimensional energy access / energy poverty measurement with corresponding energy services (Bhatia & Angelou, 2015). It does so, however, with a focus on energy supply, rather than access to services as described within the TEA. To do so, the MTF establishes a nominal set of household energy services and links these with the corresponding appliances (and cookstoves) in order to define so called *'tiers'* of household electricity supply and clean cooking access. The *tiers* reflect ordinal levels of energy supply from tier 0 (none) to tier 5 (complete). They are intended to disaggregate energy supply into its constituent components and describe improvement along each of these, rather than set a binary threshold below which one is considered *'without access'* or *'energy poor'*. The MTF describes electricity and clean cooking separately, with electricity access defined across three sub-frameworks, and clean-cooking through one. I discuss these in the following paragraphs.

MTF - Electricity

The MTF sub-frameworks for measuring electrical energy access draw from a nominal set of energy services and a selection of corresponding appliances, as shown in Figure 2.1. The five nominal power thresholds described here correspond directly to the five tiers of access across all three sub-frameworks. This table represents, therefore, the index structure for the measurement of access to electrical energy services using the MTF. This is a crucial aspect of the MTF and requires appropriate reflection from a justice-based perspective.

Typical Household Electric Appliances by Power Load

	VERY LOW-POWER APPLIANCES	LOW-POWER APPLIANCES	MEDIUM-POWER APPLIANCES	HIGH-POWER APPLIANCES	VERY HIGH-POWER APPLIANCES
Lighting	Task lighting	Multipoint general lighting			
Entertainment & Communication	Phone charging, radio	Television, computer, printer			
Space Cooling & Heating		Fan	Air cooler		Air conditioner,[a] space heater[a]
Refrigeration			Refrigerator,[a] freezer[a]		
Mechanical Loads			Food processor, water pump	Washing machine	Vacuum cleaner
Product Heating				Iron, hair dryer	Water heater
Cooking			Rice cooker	Toaster, microwave	Electric cooker

[a]*Continuous load*

Figure 2.1: The MTF - electrical energy services and corresponding appliances, source: Bhatia & Angelou (2015).

The implicit ordinal nature of energy services as per this framework is evidently driven by the estimated nominal power consumption of an *a priori* selection of household appliances. This raises two concerns when considered from a justice-based perspective. Firstly, the implicit ranking of energy services stands contra to the theoretical assessment of energy poverty from a Capabilities Approach and the irreducible nature of a set of basic energy services that all households deserve access to, as described by the Decent Living Standards. Secondly, the implicit ranking does not draw from empirical evidence of household energy needs exogenous of supply or wealth constraints. Rather, the evidence is primarily drawn from data describing supply- and wealth-constrained energy use. Both of these concerns have implications with respect to policy development in countries with energy access deficits. Jurisdictions with energy access deficits will inevitably require establishing minimum targets on the way towards complete access for all. Application of the MTF in its current form to establish these intermediate targets would mean that these would then be defined based on nominal power requirements of an *a priori* selection of appliances under supply- and wealth-constraints, rather than the immediate needs of households in the given country or region. Moreover, while these appliances and nominal power requirements may have been reasonable at the time of development, the rapid pace of technology innovation raises the question of whether tying energy access measurement to a universal set of appliances and stagnant efficiency levels can remain useful in mid to long-term electricity access planning and across vastly different contexts of implementation.

Multi-tier Matrix for Access to Household Electricity Supply

ATTRIBUTES		TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
1. Capacity	Power[1]		Very Low Power Min 3 W	Low Power Min 50 W	Medium Power Min 200 W	High Power Min 800 W	Very High Power Min 2 kW
	AND Daily Capacity		Min 12 Wh	Min 200 Wh	Min 1.0 kWh	Min 3.4 kWh	Min 8.2 kWh
	OR Services		Lighting of 1,000 lmhrs per day and phone charging	Electrical lighting, air circulation, television, and phone charging are possible			
2. Duration	Hours per day		Min 4 hrs	Min 4 hrs	Min 8 hrs	Min 16 hrs	Min 23 hrs
	Hours per evening		Min 1 hrs	Min 2 hrs	Min 3 hrs	Min 4 hrs	Min 4 hrs
3. Reliability						Max 14 disruptions per week	Max 3 disruptions per week of total duration < 2 hours
4. Quality						Voltage problems do not affect the use of desired appliances	
5. Affordability					Cost of a standard consumption package of 365 kWh per annum is less than 5% of household income		
6. Legality						Bill is paid to the utility, prepaid card seller, or authorized representative	
7. Health and Safety						Absence of past accidents and perception of high risk in the future	

[1] *The minimum power capacity ratings in watts are indicative, particularly for Tier 1 and Tier 2, as the efficiency of end-user appliances is critical to determining the real level of capacity, and thus the type of electricity services that can be performed.*

Multi-tier Matrix for Access to Household Electricity Services

	TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
Tier criteria	Not applicable	Task lighting Phone charging	General lighting Television Fan (if needed)	Tier 2 AND Any medium-power appliances	Tier 3 AND Any high-power appliances	Tier 4 AND Any very high-power appliances

Multi-tier Matrix for Electricity Consumption

	TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
Annual consumption levels, in kilowatt-hours (kWh)	<4.5	≥4.5	≥73	≥365	≥1,250	≥3,000
Daily consumption levels, in watt-hours (Wh)	<12	≥12	≥200	≥1,000	≥3,425	≥8,219

Figure 2.2: The MTF - household access to electrical energy services, source: Bhatia & Angelou (2015).

Notwithstanding these concerns, the MTF sub-frameworks for measuring electrical energy access are well-aligned across *supply*, *services* and *consumption*, as shown in Figure 2.2. The supply sub-framework describes multi-dimensional electricity supply across seven different attributes as deemed necessary to power corresponding appliances. The services sub-framework describes access to energy services from appliances arranged in an ordinal manner by power consumption. The consumption sub-framework describes annual consumption levels associated with these appliance groups and typical usage patterns.

The sub-framework for electricity supply is given the most attention in the literature and is the most detailed and developed of the three. The seven attributes are considered equally important such that the lowest performance in any of these defines the overall supply tier of the household. This assumption is arguably the best that could be made in lieu of available empirical evidence. Nevertheless, it remains entirely unproven and lacks a sound theoretical justification[1]. There are two closely related problems that arise out of this assumption. Firstly, this assumption implies that households require capacity to increase at the same rate as duration. This may simply not be the case for lower income households for whom a medium capacity (but sufficient to power their appliances) guaranteed over a 24 hours would be sufficient. This may indeed be provided at lower cost than both tier 5 capacity and supply, for instance, through off-grid standalone solar products. Secondly, this assumption implies that, across all attributes, households value improvement from, for instance, tier 4 to tier 5 at the same rate as from tier 2 to tier 3. That is, it implies the marginal utility of improving from any tier to any other tier, within each attribute, is linear. Once again this may simply not be the case for all households, or indeed the majority in a low access context. If we again take the example of lower income households, an improvement in duration from tier 0 to tier 2 might be associated with an equivalent marginal well-being shift relative to that felt with an improvement from tier 0 to tier 3. This would render the distinction between these two tiers, and subsequent policy design with these as targets, as somewhat problematic.

MTF - Clean Cooking

Measurement of household access to clean cooking solutions is somewhat analogous to the MTF household electricity supply sub-framework. The ordinal framework describes tiers distinguished by primary and secondary cooking stoves in combination with the type of fuels combusted in these. This is shown in Figure 2.3. Inherent in the tier distinction is the cooking location and ventilation, which in the case of solid fuel use has particular implications for indoor and household air quality and associated health impacts. For certain non-solid fuels, specifically biogas, LPG, electricity, ethanol, natural gas, and solar (BLEENS), emissions and efficiency performance are considered largely independent of stove technology and superior to those of other fuels.

The tier thresholds in this matrix are set to be consistent with WHO's indoor air quality (IAQ) guidelines that are based on an assessment of the health risks associated with exposure to cooking related emissions. This provides some theoretical

[1]A detailed review of the literature discussing this limitation can be found in Paper 1, (Pelz, Pachauri, & Groh, 2018).

justification for the thresholds within each tier. Nevertheless, both national energy access planning and global agenda setting using this sub-framework has its challenges.

Multi-tier Matrix for Measuring Access to Cooking Solutions

ATTRIBUTES

		LEVEL 0	LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4	LEVEL 5
1. Indoor Air Quality	$PM_{2.5}$ (µg/m³)		[To be specified by a competent agency, such as WHO, based on health risks]	[To be specified by a competent agency, such as WHO, based on health risks]	[To be specified by a competent agency, such as WHO, based on health risks]	< 35 (WHO IT-1)	< 10 (WHO guideline)
	CO (mg/m³)					< 7 (WHO guideline)	
2. Cookstove Efficiency (not to be applied if cooking solution is also used for space heating)			Primary solution meets Tier 1 efficiency require-ments [to be specified by a competent agency con-sistent with local cooking conditions]	Primary solution meets Tier 2 efficiency require-ments [to be specified by a competent agency con-sistent with local cooking conditions]	Primary solution meets Tier 3 efficiency require-ments [to be specified by a competent agency con-sistent with local cooking conditions]	Primary solution meets Tier 4 efficiency require-ments [to be specified by a competent agency con-sistent with local cooking conditions]	
3. Convenience:	Fuel acquisition and preparation time (hrs/week)			< 7	< 3	< 1.5	< 0.5
	Stove preparation time (min/meal)			< 15	< 10	< 5	< 2
4. Safety of Primary Cookstove	IWA safety tiers		Primary solu-tion meets (provisional) IWA Tier 1 for Safety	Primary solu-tion meets (provisional) IWA Tier 2	Primary solu-tion meets (provisional) IWA Tier 3	Primary solution meets (provisional) IWA Tier 4	
	OR Past accidents (burns and unintended fires)					No accidents over the past year that required professional medical attention	
5. Affordability						Levelized cost of cooking solution (inc. cookstove and fuel) < 5% of household income	
6. Quality of Primary Fuel: variations in heat rate due to fuel quality that affects ease of cooking						No major effect	
7. Availability of Primary Fuel						Primary fuel is readily available for at least 80% of the year	Primary fuel is readily available throughout the year

Figure 2.3: The MTF - household access to clean cooking solutions, source: Bhatia & Angelou (2015).

Firstly, guidance on how to practically implement the measurement of each attribute and overall tier solution is less developed. The framework proposes three potential approaches - through direct measurement; mathematical modelling using information about household characteristics, cooking stove type and practices; or through a broad categorization of cookstove types and assumptions about cooking practices. Given the wide variety of cooking stove and fuel combinations in use globally and the widespread practice of fuel stacking, the MTF's guidance on how a particular stove is to be allocated to a particular tier, and in the case of multiple stoves in use by a single household, how these can be assessed together to determine an overall tier rating of a household is insufficient. At a minimum, clearer guidelines on these allocation rules would be useful to national planners to avoid subjective interpretation and application of these.

Secondly, the consistency with the WHO IAQ standards as well as the cookstove performance standards developed by the International Workshop Agreement (IWA) is a definite advantage of the approach. However, only the top tiers 4 and 5, as defined in the framework are consistent with IAQ standards that significantly reduce the health risks of cooking emissions. A similar critique to that discussed in measuring household electricity supply applies here. Household well-being is evidently not linearly associated with the tier definition, as is implied in the framework. National planning in countries with severe deficits, which is the vast majority in the Global South, may require intermediate goals. Using this framework, intermediate goals will not reflect linear improvements to household well-being, especially given the practical measurement challenges described above. Rather, transitions to at least tier 4 or tier 5 reflect a step-change towards significant reductions to health risks of cooking emissions, whereas below this the well-being improvements related to overall tiers are at best muddled and at worst arbitrary.

2.3 Global Goals and National Targets

It is evident that binary connection-based global goals and national targets are lagging far behind developments in multi-dimensional energy access measurement approaches. It is also evident that while each of the multi-dimensional frameworks has its strengths and weaknesses, none present a clear and practical way forward in terms of measurement for national policy development or global agenda setting. I now discuss the challenges limiting the application of these frameworks for benchmarking energy access rates and propose ways forward.

2.3.1 Defining national energy access aggregates

A summary of the three contemporary approaches for evaluating multi-dimensional energy access is shown in Table 2.5. Thus far the discussion has focussed on how these approaches measure energy access or poverty in a given household. The intention is naturally not to measure access levels for a single household but rather to benchmark levels of access across a region or indeed a country. Here, each of the approaches proposes an alternative method for aggregating household-level outcomes to establish regional or national access rates. The MEPI requires a two step process. First, the total energy service deprivation for all households with deprivation above the threshold value is averaged to define the population *energy poverty intensity* - A. Here, the use of arithmetic mean aggregation combined with the energy service weighting discussed earlier is vulnerable to outliers and has potential to hide the drivers of energy poverty in its aggregate form. Next, the share of households determined energy poor is calculated, taking the ratio of households exceeding the threshold value, termed *the headcount ratio of energy poverty* - H. The MEPI aggregate is finally calculated such that $MEPI = H \times A$ and is intended to capture both the extensive and intensive margins of energy poverty as an aggregate index.

The TEA proposes no specific method of aggregation. Instead the share of population within each separate level of energy supply (ESI) and use (MSHEA) is presented as a dashboard or using a form of radar chart visualisation. While this aligns most closely with the intention of embracing complexity, the ESI and MSHEA are not aligned in their definition of the levels of access. Moreover, the in some cases quite complex and other cases qualitative individual levels within the two sub-frameworks do not provide sufficient guidance on intermediate goals or a minimum level of access commonly required for policy development.

The MTF proposes the aggregation of a distribution of ordinal tiers across a population into a single cardinal Access Index (AI) through weighting of tiers such that $AI = \sum_{k=0}^{5}(20 \times P_k \times k)$. P_k is the proportion of population at tier k, and k is the tier number from 0 to 5. This aggregate distributes linearly increasing weights from Tier $0 = 0$, to Tier $5 = 100$ in order to preserve the ordinal nature of the Tier-based distribution of a population. That is, as discussed earlier, it is assumed that moving the same distance between any two tiers provides an identical improvement to household well-being. The problem with this assumption is, in fact, already noted by the authors who state that an evaluation of weights assigned to each Tier should be conducted at the national level, however, no standard methodology describing how this should be done has been provided.

2.3.2 Adapting and simplying the MTF

Of the three candidates, the MTF has found most widespread acceptance as a measurement framework and has been embraced by Sustainable Energy for All (SE4ALL). Nevertheless, even this success is currently limited to a few partner countries with whom SE4ALL is working, such as Kenya, where the MTF has been used to establish multi-dimensional national energy access targets beyond connections to a modern energy source. Moreover, five years following the development of the MTF, SDG 7.1: *"by 2030, ensure universal access to affordable, reliable and modern energy services"*, remains measured by household connection to a modern energy source. Broader take-up of the framework is potentially limited by the prescriptive nature of tier definitions within the sub-frameworks and the complexity this entails for national statistical offices with respect to data collection.

It is here that a distinction between measurement objectives at the national and

Table 2.5: A comparison of multi-dimensional energy access and energy poverty measurement frameworks, source: Pelz, Pachauri, & Groh (2018)

	TEA	MEPI	MTF
Definition	The ESI separates energy supply across fuels, electricity, and mechanical power needs. The MSHEA combines electricity, cooldng, and heating/cooling services into one matrix.	Evaluates deprivation across a normative set of basic household energy service needs.	Separates energy services across household, productive and community needs as well as electricity, cooking, and heating services.
Measurement	Requires detailed survey data. The ESI links energy supply with binary access to energy carriers and capabilities. The MSHEA links energy access to related fuel consumption and capabilities.	Uses available DHS survey data. Relies on proxy measures including appliance ownership and binary access to energy carriers.	Requires detailed survey data. Establishes a strong link between energy service measurement and appliance/stove ownership.
Dimensions	The ESI does not explicitly describe dimensions of energy supply, whereas the MSHEA defines a unique set of dimensions for each energy service.	Does not describe specific dimensions or attributes.	Defines uniform dimensions (attributes) across each measurement matrix.
Thresholds	The ESI provides largely qualitative tier-based thresholds (0-5) for energy supply based on access to energy carriers and capabilities. The MSHEA establishes distinct qualitative and quantitative minimum thresholds for access to specific energy services.	Establishes the multidimensional energy poverty cutoff used in aggregation.	Provides largely quantitative tier-based thresholds (0-5) based on a selection of typical appliances for electricity, and indoor air quality of stoves for cooling.
Aggregation	Encourages a disaggregate analysis of both ESI and MSHEA.	Uses normative weighting for household-level aggregation alongside the cutoff. Suggests a simple average aggregate for a gap analysis of energy service deprivation across a population.	Uses a worst-performing dimension rule for ordinal aggregation at the household level and for gap analysis across a population. Suggests linear conversion of ordinal framework into cardinal Access Index across a population.

Note:
MEPI, Multidimensional Energy Poverty Index; MTF, Multitier Framework; TEA, Total Energy Access

global levels might prove useful, as shown in Figure 2.4. Tracking progress towards SDG 7.1 at the global level will most likely require some form of consolidation to simplify the measurement framework while retaining its meaningfulness. At the national level, benchmarking access for the purposes of planning and policy development will require the freedom to adapt or select from measurement dimensions and thresholds in order to truly capture the nature of energy poverty and bottlenecks to improvement in a specific country context. This argument is not necessarily new or controversial. The inception report of the MTF already describes different levels of application of the framework and corresponding survey requirements, however the discussion falls short of expressing concrete steps towards a separation of these measurement and tracking objectives and what is required for each.

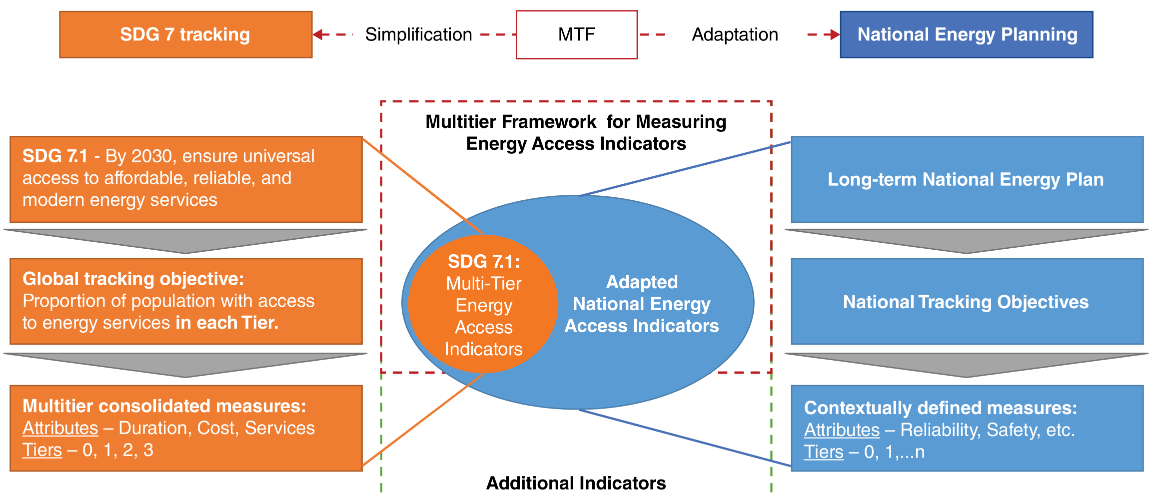

Figure 2.4: Global and national level energy access tracking with the MTF, source: Pelz, Pachauri, & Groh (2018)

Simplification of the MTF for SDG 7.1 tracking purposes requires selecting key dimensions and thresholds such that they reflect a universal minimum standard that governments should strive to provide every household. This should be aligned with the Capabilities Approach and could draw from the universal satisfiers defined under the Decent Living Standards. However they are selected, multi-dimensional indicators to measure progress towards SDG 7.1 must also remain practical and acceptable enough to form a permanent sub-component of existing data collection efforts at the country level. Assuming a universally acceptable definition of multi-dimensional energy poverty for SDG 7.1 tracking purposes, national energy planners would then have the freedom and responsibility to develop a suitably complex, politically and socially acceptable national tracking framework drawing from the needs in their context, while still reporting standard dimensions for global tracking and comparison. With these modifications in mind, the MTF in its current form should be seen more as a collection of potential dimensions and suggested thresholds that can be chosen from depending on which are most applicable to capture the real nature of energy poverty for the given tracking objective.

In the subsequent chapters, the empirical work will tackle some of the gaps and limitations described here in order to propose improvement of multi-dimensional measurement approaches for guiding progress towards target SDG 7.1. This includes testing of assumptions inherent in the MTF as well as proposing and applying multi-dimensional measures for both sub-national and cross-country tracking.

Chapter 3

Measuring Supply and Consumption

3.1 Household electricity supply and consumption in rural Northern India

Reliable electricity supply is a prerequisite of but not sufficient for household access to modern energy services. As discussed in Chapter 2, it is the access to these services, rather than the electricity supply, that satisfies desired *functionings* or end-uses associated with household well-being. Often these two distinct aspects are conflated, such that access to the national grid is considered the prime objective, with no thought given to the affordability, reliability or indeed use of the supply.

The MTF is a crucial step forward from this status-quo as it provides a pathway to move beyond a focus on grid-connections alone towards providing decent supply from a range of technologies including decentralised and off-grid electricity supply solutions. It does so foremost by measuring multi-dimensional attributes of supply and setting tier thresholds for these. The disaggregate analysis enabled by the MTF can reveal potential supply constraints and inequities hidden by binary grid-connection rates. Furthermore, the MTF enables the integration of all technologies that satisfy these tiers into national energy access plans. Such technologies can include decentralised and off-grid renewable sources of electricity, such as solar home systems and micro-hydropower plants. Both of these measurement advances are important steps to move towards equitable energy service provision. These advances are, however, not without their own challenges.

Firstly, the MTF sub-framework for measuring household electricity supply defines a set distinct attributes and tiers that are aggregated such that the lowest tier across all attributes captured within the framework defines the overall household electricity supply tier. This assumption is contested[1] and may incorrectly capture the value households place on distinct attributes of supply, providing conflicting data for regulatory and policy intervention. Secondly, while the normative justice-based ap-

[1]See Paper 2 for a review of the pertinent literature.

proaches discussed in Chapter 2 provide some guidance on defining which *functionings* and therefore which energy services could be considered essential, such measures have not yet been considered in energy access measurement or policy development. Access to energy services is proxied in the MTF by sub-frameworks for household energy consumption and the ownership of appliances of a specific power rating, both of which are not nearly as developed as the supply sub-framework. A transition from purely supply oriented measurement towards household energy service utilisation measurement could benefit from empirical evidence describing use patterns and how these are linked with supply or wealth constraints.

These considerations led to two research questions that guide the first empirical paper in this chapter. The first asks whether the MTF lowest tier aggregation approach correctly reduces multi-dimensional supply attributes into a single characteristic. The second explores these results hold across distinct energy services. This work is conducted using the ACCESS dataset, consisting of household and village surveys representative of rural areas in six contiguous states across northern India. The surveys were gathered in two waves, in 2014-15 (N = 8563 in 714 villages) and 2018 (N = 9072 in 756 villages).

3.1.1 Linking distinct electricity supply attributes and use

Are any two attributes of electricity supply equally related to household utilisation? The first question tests the assumption built in to the MTF aggregation calculation. I focus on two attributes, the typical daily supply hours and the typical monthly outages. These two attributes are selected as they are both available with sufficient variation in the dataset. The capacity attribute was not selected as this not able to be determined in the original scale as defined by the MTF, requiring instead the assumption that connection to the national grid ensures satisfactory capacity and all others do not. The analysis is conducted on the balanced panel subset of households with a grid-connection in both survey waves (N = 10,556).

The total distinct energy services used by households is then regressed on these two attributes of supply. The former is defined by assigning appliances owned by households to the following distinct electrical energy services: *Lighting, ICTs, Entertainment, Fans, Refrigeration, Thermal Loads, Mechanical Loads and Cooking.* Correlation plots are provided in Figure A.1 in Appendix A, for the balanced panel subset of grid-connected households. Summary statistics describing the full (unbalanced) ACCESS dataset can be found in the appendices of Paper 2. Linear regression analysis is applied to test the relationship between the two distinct attributes of supply and use. Formally, the null hypothesis here is that both supply attributes have no statistically significant relationship with energy service usage. More specifically, we are interested to understand whether there is a difference between these two attributes and their relationship with household energy service usage. Both survey wave and household fixed effects as well as a series of covariates are selected in an attempt to isolate as far as possible the relationship between supply attributes and total energy services used. The results are provided in Table 3.2, with the adjustment of standardizing the continuous variables. The coefficients can be interpreted

Table 3.1: Summary statistics: ACCESS grid-connected panel subset (N = 10,556).

Variable	Mean_2015	Mean_2018	SD_2015	SD_2018	SD_pooled
Total Services	3.44	3.81	1.45	1.34	1.41
Daily Supply Hours	12.78	15.56	6.09	5.22	5.84
Monthly Outages	3.81	2.10	4.95	3.33	4.29
Household Size	6.77	6.22	3.63	3.32	3.49
Pucca House	0.41	0.48	0.49	0.50	0.50
10th Grade +	0.42	0.35	0.49	0.48	0.49
Monthly Exp.	5711.87	6765.60	4239.87	4774.88	4544.82
BPL/AAY Card	0.45	0.50	0.50	0.50	0.50
SC/ST	0.27	0.28	0.44	0.45	0.45
Time to city	19.31	19.31	19.41	19.41	19.41
Village Shops	13.99	13.71	11.30	12.90	12.13

as *"an increase of one standard deviation in supply hours or outages was related to a β standard deviation change in the distinct energy services used"*. These changes can be related back into original units using the standard deviations presented in Table 3.1 if desired.

The results suggest that variation in supply hours is statistically related to variation in the distinct energy services used, while variation in supply outages is not. This also holds if either supply hours or outages are excluded from the model. Formally, we could reject the null hypothesis with respect to supply hours, but we could not reject the null hypothesis that with respect to supply outages. This would suggest that aggregating these two distinct attributes of supply by the lowest performing would therefore not correctly reflect the level of service as perceived by the household. Nevertheless, overall the coefficients remain quite small and it seems that household wealth factors are much more related to energy services utilisation than electricity supply constraints, conditional on having access to electricity.

This model specification is vulnerable to reverse causation as has been discussed at length and best summarised by Lee, Miguel, & Wolfram (2020) as well as time-variant unobserved heterogeneity. Firstly, if one were to argue that the variation in supply hours was driven by energy service use (e.g. appliance purchase trends motivated supply quality improvements), the two-way fixed-effect model specification would not correct the positive bias in our estimates. Secondly, if one were to argue that unobserved factors correlated with electricity supply quality and appliance ownership were time-variant, (e.g. heterogeneous commercial activity outside of the household that might have attracted more attention from the state electricity company in terms of supply quality and made appliances more readily available between survey waves), this would would bias the estimates in the positive direction. Nevertheless, as we are comparing across two attributes of supply that both ought to be affected by this bias, comparing across their coefficients requires perhaps slightly less caution.

Table 3.2: Main results: ACCESS grid-connected panel subset (N = 10,556), testing the relationship between electricity supply hours, outages and household utilisation .

Dependent Variable:	Total Distinct Energy Services			
Model:	(1)	(2)	(3)	(4)
Variables				
Daily Supply Hours	0.096***	0.055***	0.062***	
	(0.013)	(0.015)	(0.014)	
Monthly Outages	-0.008	-0.0008		-0.012
	(0.009)	(0.011)		(0.011)
Household Size	0.058***	0.067***	0.069***	0.066***
	(0.011)	(0.014)	(0.014)	(0.014)
Monthly Exp.	0.165***	0.119***	0.118***	0.121***
	(0.014)	(0.017)	(0.016)	(0.017)
10th Grade +	0.335***	0.196***	0.199***	0.195***
	(0.018)	(0.028)	(0.027)	(0.028)
Pucca House	0.406***	0.306***	0.315***	0.304***
	(0.022)	(0.028)	(0.028)	(0.028)
BPL/AAY	-0.199***	-0.123***	-0.129***	-0.126***
	(0.018)	(0.026)	(0.025)	(0.026)
SC/ST	-0.212***			
	(0.024)			
Fixed-effects				
Year (2)	Yes	Yes	Yes	Yes
Village (670)	Yes			
Household (5,278)		Yes	Yes	Yes
Fit statistics				
Observations	10,267	10,267	10,519	10,267
R^2	0.45370	0.76507	0.75857	0.76438
Within R^2	0.20250	0.08181	0.08580	0.07909

Clustered (Village) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

3.1.2 Exploring energy services utilisation

"What distinct energy services are used by rural households and how is this linked with supply constraints?" In light of the relatively weak relationship identified in the previous research question, we now want to understand whether electricity supply hours were indeed a constraint for household access to certain energy services (such as those that were affordable for households), or whether the weak relationship holds evenly across all services. Figure 3.1 shows the share of distinct energy service use across the full ACCESS dataset as well as the balanced grid-connected panel subset. It is evident that the majority of grid-connected households in the sample primarily have access to Lighting, ICTs, Fans, and Entertainment (Televisions, etc.). The remaining services are utilised by at or less than 10% of the sample in 2018.

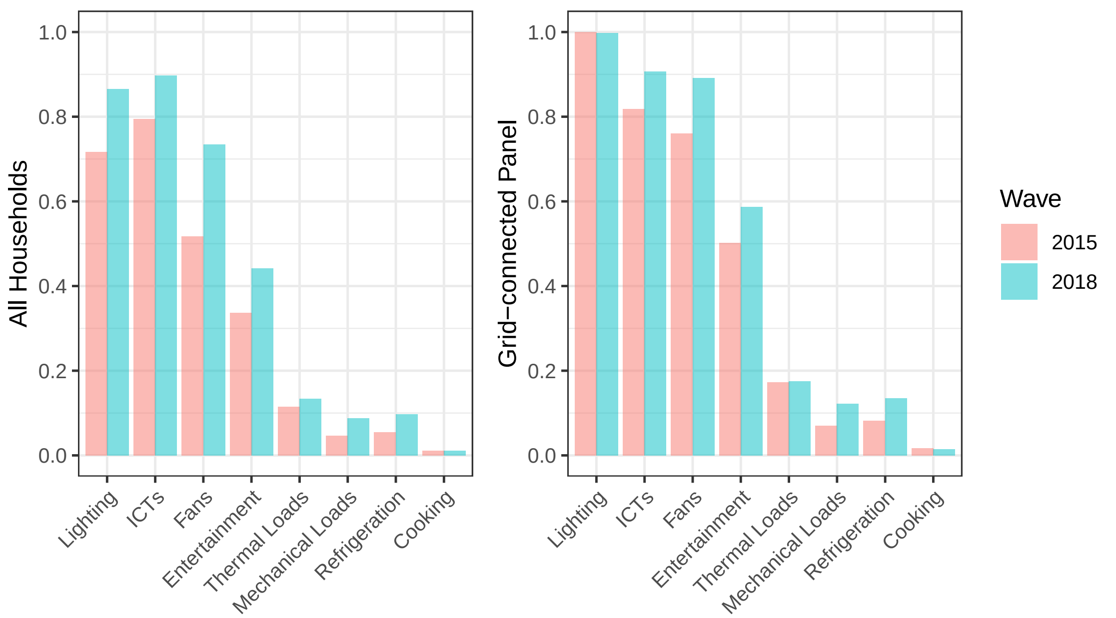

Figure 3.1: Summary statistics: ACCESS full and balanced panel subset, aggregate rates of energy service utilisation.

Are these distinct access rates heterogeneously related to supply constraints? To answer this, groups are created that describe (change in) household access to each energy service. Table 3.3 provides counts of households in groups defined by their access to each energy service across both survey waves. As a reminder, this reflects the grid-connected panel subset of households (N = 10,556 observations or N = 5,278 unique households). Here we see that household access to *Lighting* and *Cooking* services hardly shifted and describes the two extremes - almost complete access, and almost no access. Access to the remaining services shifted somewhat between survey waves. This variation is exploited to understand differences in supply duration between the groups of households that gained access to an energy service (*GainedAccess*) against those that did not (*NeverAccess*) or those that lost access (*LostAccess*). Linear regression is used with the *Supply Hours* as the dependent variable for a series models

Table 3.3: Summary statistics: ACCESS grid-connected panel subset (N = 10,556), groups of households by overall access to energy services between 2015-2018.

Energy Service	AlwaysAccess	GainedAccess	LostAccess	NeverAccess
Lighting	5,261	1	16	NA
ICTs	4,244	617	275	142
Fans	3,367	1,206	255	450
Entertainment	1,910	1,060	722	1,586
Thermal Loads	373	542	654	3,709
Mechanical Loads	198	519	278	4,283
Refrigeration	254	502	230	4,292
Cooking	4	66	99	5,109

reflecting each energy service. The group of households that always had access is omitted and used as a benchmark to compare against. Both survey wave and village fixed-effects are applied. The latter is the selected at this level to balance the trade-off between reducing the influence of confounders and ensuring sufficient variation in our key variables within these groups. Selected model coefficients are shown in Figure 3.2. All continuous variables are standardised once again and Table 3.1 can be used to translate this back to the original units. The coefficients can be interpreted as *"being in group X was related to a β standard deviations difference in supply hours, relative to the group of households that always had access to the energy service"*. The full model specification, performance metrics and results are provided in Table A.1 in Appendix Section A. The results of the linear regression analysis are broadly consistent with the first research question results, indicating that relative to households that always had access to any of the energy services tested between the survey waves, households that remained without access also received lower average daily supply hours (except for those with to ICTs). The results should however be considered with caution in general, given the size of the coefficients and considering the groups that gained or lost access. While the estimates suggest that households losing access to fans and televisions also had lower supply duration on average, the coefficients for those that gained access are also somewhat mixed. In reflecting on these results, it is important to recognise that the confidence intervals remain wide and care should be taken not to consider this a causal model. The issues of reverse causality and time-variant heterogeneity discussed earlier are perhaps more pronounced here. Overall, despite these weaknesses in model specification, what we can draw from these results is that the conditional mean supply duration was different between the groups that always had access to energy services and those that didn't. Moreover, it appears that this difference is somewhat heterogeneous across energy services. Lighting is ubiquitous with a grid-connection, whereas ICTs are dependent more on wealth than supply differences. Televisions and fans are typically devices that are owned by households with better supply, although this is quite a weak relationship and shared across the other remaining energy services. Once again, it would appear that factors beyond supply constraints are strongly modifying household energy service usage likelihoods.

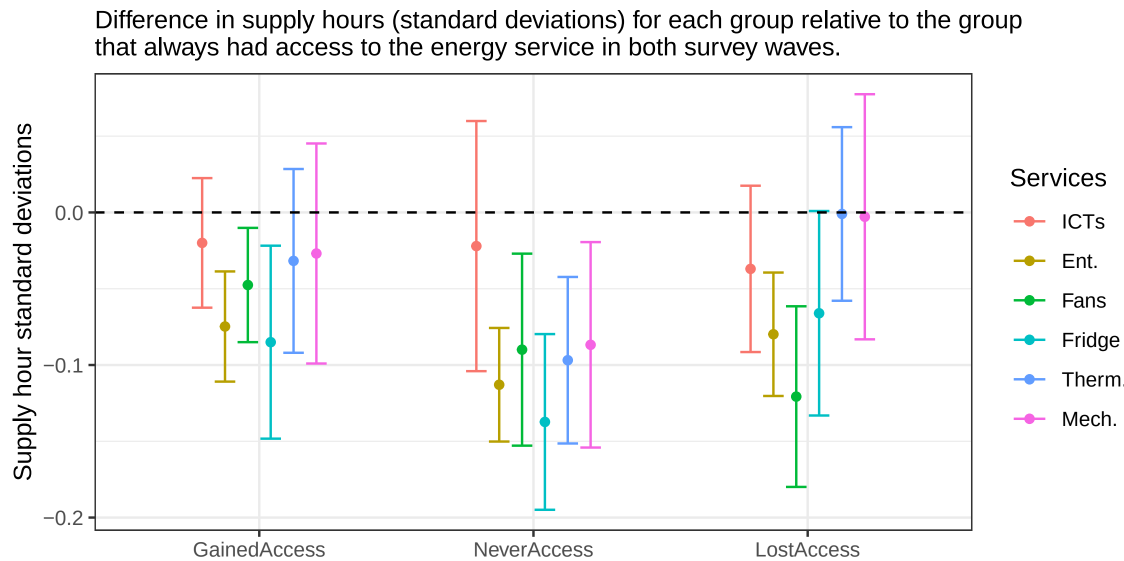

Figure 3.2: Main results: ACCESS grid-connected panel subset (N = 10,556), comparing differences in conditional mean supply hours relative to households that always had access to the energy service in each model.

3.2 Productive electricity use among MSEs in rural Northern India

Alongside household electrification, rural electrification discourses inevitably include so called *productive* uses of electricity, whether as specific targets of an intervention or embedded in a theory of change. The literature describing rural enterprises and productive electricity use is, however, both sparse and mixed. Specifically in emerging economies, prior work suggests that electricity supply is an important pre-requisite but not sufficient to foster rural enterprise growth[2]. Continuing on the theme of the work thus far, this section provides empirical evidence describing the relationship between rural electricity supply and micro- and small-enterprise (MSE) electricity use in rural northern India.

The analysis in this section is conducted using the SPI-ISEP REDI dataset, consisting of a cross-sectional survey of 2,004 rural small- and micro enterprises from 200 similar rural revenue villages in Bihar, Uttar Pradesh, Rajasthan and Odisha. 200 revenue villages were selected as part of a study designed to measure rural electricity demand and understand the customer perspective towards mini-grid electricity and grid electricity. Mini-grid revenue villages were sampled from a master list of 91 Smart Power India mini-grid intervention revenue villages across the states surveyed, where

[2]See Paper 3 for a review of the pertinent literature

Table 3.4: Summary statistics: REDI dataset, key village-level aggregates by sample group.

Variable	Grid (Franchise)	Grid (Public)	Grid (Public) + MG
Villages Sampled	54.00	96.00	50.00
Mean Households	938.35	937.29	1649.68
Mean Share BPL	0.45	0.51	0.63
Mean Marketplaces	1.26	1.05	1.08
Mean Grid Hours	19.40	14.91	13.59
100% Hamlet Elec.	0.96	0.89	0.62
Grid Conn. Cost	1655.69	1898.77	1899.79
MG Conn. Cost	NaN	NaN	696.33

these decentralised systems co-exist in parallel to the national grid. These mini-grids range from 30-60 Kilowatt-Peak (kWp) in size and are operated by local energy service companies. Alongside the mini-grid interventions, the survey also explored the effects of privatisation of the national grid distribution network, and sampled from a list of revenue villages in Odisha where private distribution franchises operated the local grid.

3.2.1 Linking grid supply quality with MSE connection and use

"Is grid supply quality related to rural MSEs propensity to connect to the national grid and their electricity consumption more broadly?" This question is motivated by Tables 3.4 & 3.5 which indicate that although all villages in the sample are grid-connected (to different levels of completeness), less than two-thirds of MSEs have secured a grid connection. Might differences in grid supply reliability factor into this decision making process or are other constraints hindering enterprise connection and use? Is a grid-connection even desirable for all types of MSEs? Outcomes to these questions could add to the discourse around electrification measurement and the role of off-grid technologies alongside grid-extension.

The correlation between village grid supply hours[3] and enterprise propensity to connect and electricity consumption more broadly is tested using linear regression analysis. A linear probability model and a linear regression model is used. Both state and enterprise category fixed-effects are applied alongside a set of variables that adjust for confounding within enterprise groups and states. The motivation for the enterprise-category fixed effects is that we are interested in the relationship between grid supply and MSE connection and use in aggregate terms, that is, for the average enterprise in the sample, rather than a specific subset[4]. All binary variables are left as

[3]The reported average grid electricity supply duration hours reflect the average of stated winter and and summer supply duration as reported by the village leaders during the community survey. This is not expected to be biased by enterprise characteristics.

[4]See Paper 3 for a further detail on enterprise categories in the REDI survey dataset.

Table 3.5: Summary statistics: REDI dataset (N = 2,004), relevant village- and enterprise-level variables.

	Mean	SD	Min	Max	Observations
MSE grid connected	0.65	0.48	0.0	1.00	2004
MSE uses OG backup	0.43	0.50	0.0	1.00	2004
MSE monthly kWh	32.30	140.03	0.0	2979.80	2004
Village grid supply hours	15.79	4.33	2.5	24.00	2004
Village households	1114.85	801.58	180.0	5750.00	2004
Village share of BPL households	0.52	0.33	0.0	1.65	1994
Village marketplaces	1.11	0.41	1.0	4.00	2004
Village hamlets electrified	0.84	0.37	0.0	1.00	2004
MSE floor area	142.42	246.01	9.0	7200.00	2004
MSE salaried employees	0.16	0.61	0.0	10.00	2004
MSE building pucca	0.69	0.46	0.0	1.00	2004
MSE building owned	0.62	0.49	0.0	1.00	2004

is, and continuous variables are standardised as before. A correlation plot is provided in Figure A.2 of Appendix Section A. The results are provided in Table 3.6. The coefficients for models 1-3 can be interpreted as *"an increase of one standard deviation in the independent variable (or presence of a dummy variable) is related to a $\beta \times 100$ change in the likelihood (in percentage-points) that the enterprise is grid-connected"*. The coefficients for models 4-6 can be interpreted as *"an increase of one standard deviation in the independent variable (or presence of a dummy variable) is related to a β standard deviation change in the enterprise electricity consumption"*[5]. The results show that village average grid hours has a positive but statistically insignificant relationship with both enterprise grid connection likelihoods and enterprise electricity consumption more broadly. Due to the wide confidence bands of these point estimates, a general trend indicating that better grid supply reliability is associated with higher incidence of enterprise grid connection and electricity consumption more broadly cannot be explicitly inferred and suggests instead that these relationships are modified by the type of enterprise, among other factors.

The regression analyses are useful insofar as they provide a more nuanced description of grid-connection likelihoods and supply hours than that shown by grouped summary statistics of the cross-sectional data. Nevertheless, while effort is made to reduce the effects of potential confounders, this does not reflect an identified causal model and thus conclusions should be drawn with care. Notwithstanding these concerns, confounders are likely to positive bias our estimates as discussed in the household panel model in the earlier section. It is therefore even more notable that MSE connection likelihoods are not conclusively linked to grid supply constraints. In the next research question, differences in enterprise characteristics and actual electricity use is explored in further detail.

[5] Robustness checks are included in Paper 3.

Table 3.6: Main results: REDI dataset (N = 2,004), testing the relationship between grid supply hours and MSE connection and use.

Dependent Variables:	Grid connected		Monthly kWh	
Model:	(1)	(2)	(3)	(4)
Variables				
Village average grid hours	0.052*	0.043	0.050*	0.040*
	(0.028)	(0.028)	(0.029)	(0.022)
Village households	-0.014	-0.016	-0.028*	-0.015
	(0.018)	(0.016)	(0.014)	(0.013)
Village marketplaces	0.0003	-0.0007	0.010	0.008
	(0.012)	(0.011)	(0.020)	(0.016)
All hamlets grid connected	0.038	0.032	0.036**	0.019*
	(0.025)	(0.025)	(0.014)	(0.009)
Village share BPL households	-0.028**	-0.020	0.002	0.018
	(0.013)	(0.013)	(0.021)	(0.015)
Floor area		0.028**		0.035
		(0.012)		(0.030)
Salaried employees		0.030***		0.046*
		(0.010)		(0.027)
Building owned		0.049*		0.060**
		(0.026)		(0.028)
Building pucca		0.242***		0.131**
		(0.041)		(0.056)
Fixed-effects				
State (4)	Yes	Yes	Yes	Yes
Enterprise Category (7)		Yes		Yes
Fit statistics				
Observations	1,994	1,994	1,994	1,994
R^2	0.24578	0.31869	0.00762	0.30958
Within R^2	0.02359	0.09996	0.00350	0.01432

Clustered (District) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

3.2.2 Describing rural MSE productive electricity use

How do rural MSEs actually use their electricity supply?. The motivation here is to provide further context to the regression results in the previous section, but also to describe rural productive electricity use more broadly. As electricity consumption was not captured across all firms, a simple time-use engineering approach is used. The estimated monthly electricity consumption is based on the reported total hourly usage of each appliance type, multiplied by the reported average hourly power requirements of the appliance[6]. These appliances are aggregated into five electrical energy service categories. These include Lights, Fans, ICTs, Mechanical and Refrigeration. Energy service use is further grouped into buckets of services, reflecting none (*None*), Lights (*Light*), Lights and Fans (*Light+Fan*), and Lights, Fans and Others (*Light+Fan+*).

Energy service utilisation rates across the entire sample are shown in Fig 3.3. The energy service usage appears to be surprisingly low across the board. The majority of enterprises do not use appliances beyond lighting and fans except for those engaging in digital services such as cyber cafes and photo studios. Grid-connection appears to be moderately associated with higher energy service use than firms remaining off-grid, although this likely to be more related to enterprise wealth and type than supply constraints as discussed earlier. Figure 3.4 reduces energy service use into estimated monthly electricity consumption. As suggested by the energy service aggregates, consumption is very low across the board. The median MSE consumes less than 20 kWh per month with consumption linked closely to the buckets of energy services used. Digital firms stand out once again as those that indicated higher electricity consumption, however even among this group, the median enterprise consumes just over 30 kWh per month, or 1kWh per day.

Overall, the low levels of energy service use and electricity consumption help contextualise the linear regression results in the previous section. Most enterprises do use electricity to some extent, but we could speculate that this is not necessarily a direct input for their productive processes (with the exception of digital enterprises). The notion that electrification will increase productivity and be a natural input for all enterprises is not fully supported by the data. Rather, it would appear that for many enterprises, affordable access to lighting and space cooling providing thermal comfort to employees and customers would be sufficient for their current productive activities. This is not to say that electricity is not a pre-requisite to the growth of these businesses, but rather, that a broad-brush policy goal to provide grid-connections to all enterprises may not reflect enterprise needs, and may in fact increase costs[7]. Rather, the results underline once again that measurement of multi-dimensional supply attributes and utilisation (as well as the needs and preferences end-users) can aide in informing more efficient energy policy reform.

[6] Paper 3 contains further detail describing the energy services categories, typical corresponding appliances and the reported peak power requirement.

[7] This is discussed in more length in paper 3, including the role of off-grid standalone systems in satisfying emerging enterprise needs cost-competitively to central grid connection.

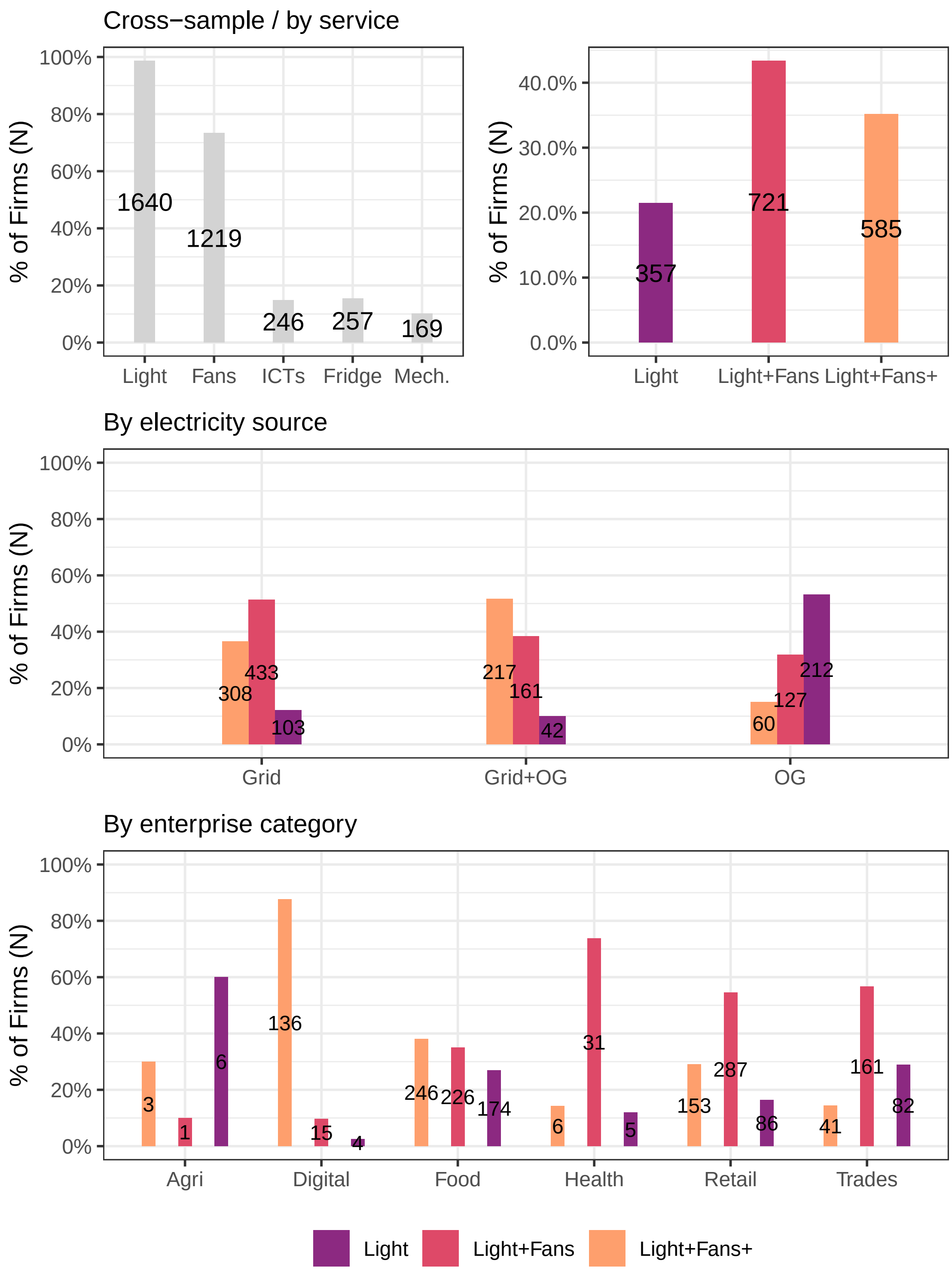

Figure 3.3: Main results: REDI dataset (N = 2,004), energy service use across sampled MSEs.

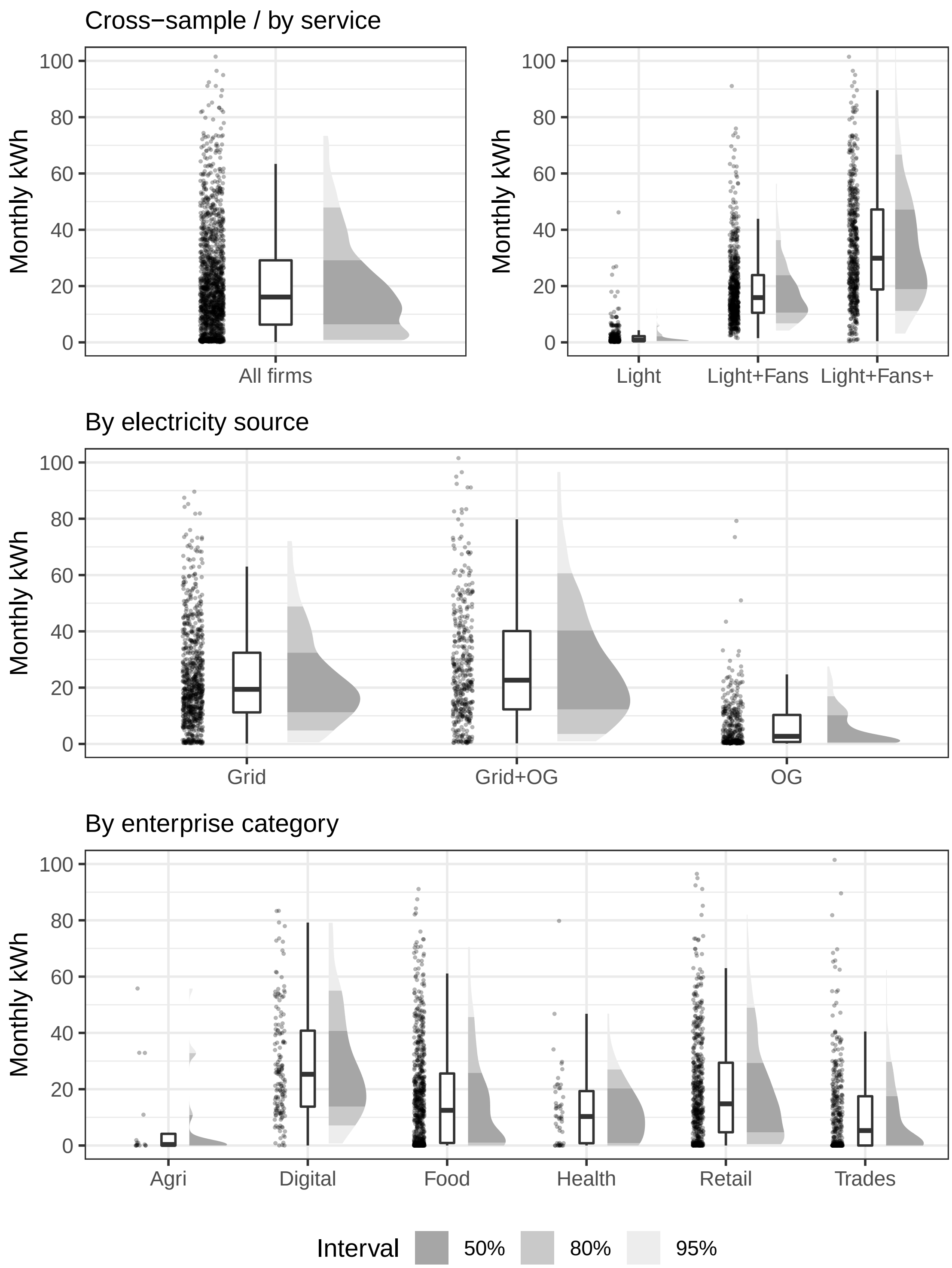

Figure 3.4: Main results: REDI dataset (N = 2,004), electricity consumption across sampled MSEs.

3.3 Capturing inequities: A case study in rural Nepal

The final section of this chapter draws from the empirical evidence thus far to describe inequities in electricity access and use from a justice-based perspective across 14 municipalities in far-eastern and far-western Nepal. This represents the first attempt at improving on the MTF and capturing both supply and use aspects of household electricity access in this project. The data analysed in this section is the result of a bespoke household survey and sampling approach designed together with local stakeholders. The approach and resulting instruments and data are described in detail in Paper 4[8]

3.3.1 Distributional and recognition justice in energy access planning

Two-thirds of the rural Nepali population have access to the national grid, while just under one third rely solely on standalone and off-grid technologies[9]. Pervasive supply quality issues in rural areas have been linked to the historically ad-hoc nature of energy supply development and lack of integrated energy access planning. Recent governance changes in Nepal have motivated national level electrification planners to work with local government stakeholders at the recently formalised Municipal level. Although national electricity network expansion remains under the remit of the central Government, it has embraced the approach of integrated energy access planning which includes consideration of all electrification technologies. This involves including municipal stakeholders in distribution network expansion planning and providing municipalities with more control over off-grid supply options within their constituency. The technical capacities of the 460 rural municipalities spread across Nepal varies greatly, however, and this challenge is amplified by the limited availability of disaggregated data at municipal level.

As the justice-based approaches discussed in Chapter 1 argue, fair and just representation is critical to overcome socio-cultural and structural inequities that may be preserved despite aggregate improvements to energy supply. Sub-nationally disaggregated data could therefore be considered a prerequisite of equitable municipal energy supply planning. This can be challenging to gather in contexts with limited administrative data availability describing the local population. This gap was approached in this work through a gridded sampling approach guided by remotely sensed population datasets and a bespoke data collection instrument.

The gridded sampling approach ensures all constituents in the municipality have equal chance of being selected to participate in the questionnaire, regardless of where they live. This is achieved by weighting each cell of a high resolution population grid

[8]Deviating slightly from Paper 4, this section includes the full analysis of all 14 municipalities, going beyond the six municipalities in the paper which were selected to simplify geographic visualisation.

[9]Paper 4 provides a more detailed literature review and discussion of the local context.

by its proportional population. This is itself is embedded in a lower resolution grid, within which all cells must contain at least one enumeration area. This maintains a representative sample at municipal level, while ensuring large sparsely populated areas of the municipality are not ignored. Further detail on the approach and the algorithm used are provided in Paper 4. The data collection instrument was designed to enable a disaggregate analysis of energy supply and use, drawing heavily from the MTF questionnaire guidelines while also capturing necessary household characteristics. The survey questionnaire captured household demographic and socio-economic characteristics, electricity access and related expenditures, appliance ownership and desire, productive activities, cooking technologies, related expenditures and preferences, asset ownership and access to finance.

Combined together, these two methods provide the data necessary for the application of justice-based approaches for measuring inequities in access to modern energy services. The distributional justice aspect is explored through the spatial disaggregation of electricity supply deficits to understand where supply inequities exist. The recognition justice element is explored through disaggregate analysis of energy supply and services utilisation across wealth groups.

3.3.2 Measuring energy supply and use

The multi-tier framework provides guidance on describing access to clean cooking solutions. As discussed in Chapter 2, however, application of these multi-dimensional tier thresholds is challenging and necessitates the use of proxy measures typically considered as the combination of cookstove and fuel. In alignment with the literature at the time of publication, access to cooking is analysed in terms of the primary and secondary stove utilised by the household, as well as their primary and secondary fuels. Clean cooking is considered as access to a BLEN stove, which in the case of the municipalities studied, primarily refers to LPG stove access. Stove stacking was not readily observed and is discussed in further detail in Paper 4. An overview of the types of stoves and fuels found in the data is provided in Table 3.7 below.

Table 3.7: Stove and fuel combinations, for the Nepal survey dataset.

Type	Description	Fuel
UCS	3-stone fire, self-built clay stove	Firewood
ICS	Mud or metallic improved cookstove	Firewood
BLEN	Liquefied petroleum gas stove / Biogas stove	LPG / Biogas

Electricity supply is disaggregated using *supply hours* as the primary indicator based on the lessons drawn from earlier work in this chapter. Supply *capacity* is also included as a secondary indicator, reflecting the safe operating capacity of the electricity supply in kilowatts. This is complemented with an analysis of energy services utilisation based on groups of energy services. The analysis here does not prescribe relative importance to a given energy service. Rather, it describes access to each group of services independently. Energy services are grouped as shown in Table 3.8.

Table 3.9: Summary statistics: Nepal survey dataset (N = 5,969), municipal-level Palma ratio and binary energy access rates.

Municipality	Palma ratio	Elec.	Grid/MG	UCS	ICS	BLEN
Aamchowk	3.16	0.97	0.14	0.78	0.21	0.01
Hatuwagadhi	6.65	0.97	0.08	0.66	0.32	0.02
Udayapurgadhi	3.92	0.95	0.20	0.86	0.10	0.05
Haleshi Tuwachung	3.09	0.97	0.60	0.52	0.41	0.07
Maanebhanjhyang	3.54	0.98	0.48	0.66	0.24	0.10
Gaurigunj	2.22	0.98	0.85	0.77	0.00	0.23
Jahada	0.93	0.89	0.83	0.94	0.00	0.06
Miklajung	0.73	0.97	0.42	0.61	0.33	0.06
Bithadchir	0.89	0.92	0.03	0.98	0.00	0.02
Kedarseu	0.84	0.94	0.10	0.94	0.05	0.01
Dogadaker	1.20	0.95	0.31	0.97	0.02	0.01
Chure	0.81	0.92	0.17	0.97	0.03	0.00
Baddikedar	0.80	0.92	0.03	0.95	0.05	0.00
Badimalika	0.96	0.73	0.59	0.89	0.07	0.04
Shuklaphanta	1.15	0.98	0.94	0.62	0.02	0.36

The literature indicates that lighting and communications are typically ubiquitous with adequate household electrification, and tend to be followed by entertainment and space cooling, with the latter depending somewhat on local climactic conditions. Other costlier and energy intensive appliances that reduce household drudgery are typically context specific and collected in the final group.

Table 3.8: Energy services and appliances, for the Nepal survey dataset.

Energy Service	Appliance	Energy Service Group
Lighting	LED Room Lighting	Lighting and communications
ICTs	Mobile Phone (Feature)	Lighting and communications
ICTs	Smart Phone / Tablet	Lighting and communications
ICTs	Radio	Lighting and communications
Entertainment	Laptop	Ventilation and entertainment
Entertainment	Television	Ventilation and entertainment
Ventilation	Fan	Ventilation and entertainment
Mechanical Loads	Blender/ Mixer	All others
Refrigeration	Fridge	All others
Thermal Loads	Electric Iron	All others
Thermal Loads	Electric Rod Water Heater	All others
Cooking	Rice Cooker	All others

Table 3.10: Summary statistics: Nepal survey dataset (N = 5,969), municipal-level electricity supply attribute means and energy service access rates.

Municipality	Hours	Capacity	Lights+Comms.	Vent.+Ent.	All others
Aamchowk	9.53	0.15	0.93	0.02	0.01
Hatuwagadhi	15.63	0.10	0.98	0.02	0.01
Udayapurgadhi	12.94	0.21	0.95	0.06	0.04
Haleshi Tuwachung	20.87	0.57	0.98	0.25	0.07
Maanebhanjhyang	12.88	0.51	0.99	0.16	0.04
Gaurigunj	21.57	0.80	0.99	0.79	0.44
Jahada	19.56	0.78	0.93	0.74	0.22
Miklajung	16.83	0.39	0.99	0.36	0.02
Bithadchir	16.56	0.05	0.95	0.02	0.00
Kedarseu	16.99	0.10	0.94	0.03	0.00
Dogadaker	18.26	0.31	0.93	0.17	0.05
Chure	17.62	0.17	0.93	0.07	0.01
Baddikedar	17.46	0.05	0.96	0.05	0.00
Badimalika	14.58	0.55	0.79	0.12	0.03
Shuklaphanta	20.98	1.22	0.96	0.90	0.37

Table 3.9 provides summary statistics of the income inequity and energy access levels across all municipalities. Income inequity is described using the Palma ratio, which aggregates the income of the top decile and divides this by the aggregate incomes of the bottom four deciles[10]. Energy access is reported purely in terms of connections to begin with. Electricity access is split into households reporting access to any electricity source, and those reporting access to the grid or a minigrid. Clean cooking access is reportedly as access to an UCS, ICS or LPG stove. Table 3.10 provides further detail of municipal electricity supply attributes. Considered across both of these tables, the Palma ratio suggests that there is some level of heterogeneity across municipalities in terms of income inequity, although any clear relationship with the Palma ratio and aggregate access to modern energy carriers and supply attributes across municipalities is not evident. This is now explored in further detail within each municipality.

Figure 3.5 compares income inequities with multi-dimensional electricity supply attributes both within and across the sampled municipalities. Here the distinct attributes of supply capacity and hours are aggregated for the top decile of households by income within each municipality, and used as the numerator over the aggregate attributes for the bottom four deciles of households by income within each munici-

[10]A Palma ratio of 1 indicates that the top decile earns four times as much as the bottom four deciles. A Palma ratio of 0.25 would suggest parity, at least at the aggregate level across the bottom four and top deciles. Cobham, Schlögl, & Sumner (2016) provide further detail on the origin of the Palma ratio and compare this with the Gini coefficient, finding support for its continued use in measuring income inequities.

pality. Essentially, this is an extension of the Palma ratio and describes whether the richest 10% of households in a given municipality also have disproportionately better electricity supply attributes than the bottom 40% of households of the same municipality. The visualisation thus plots the Palma ratio extension for supply hours against the supply capacity, showing thresholds for an *'egalitarian'* distribution of supply attributes between the top 10% and the bottom 40% using the dashed lines on each axis. This visualisation describes both the intensity of electricity supply inequities within each municipality and enables a comparison of this across all municipalities. Despite almost all households having some form of electricity access, severe inequities across both attributes of supply are evident across the sampled municipalities. Some may argue that these inequities are transitional and rather indicators of some parabolic shape informed by literature that explains inequities as necessary for development. This sample of municipalities was not randomly selected and is thus not representative of a broader group, hindering any speculation on this hypothesis. Nevertheless, the diverging colour gradient in the visualisation also provides an indication of the penetration of the national grid / local micro-hydro network in the municipality. Higher inequities (moving further to the top right of the figure) would be expected at the mid-point of this colour scale, which does not appear to be reflected in the data.

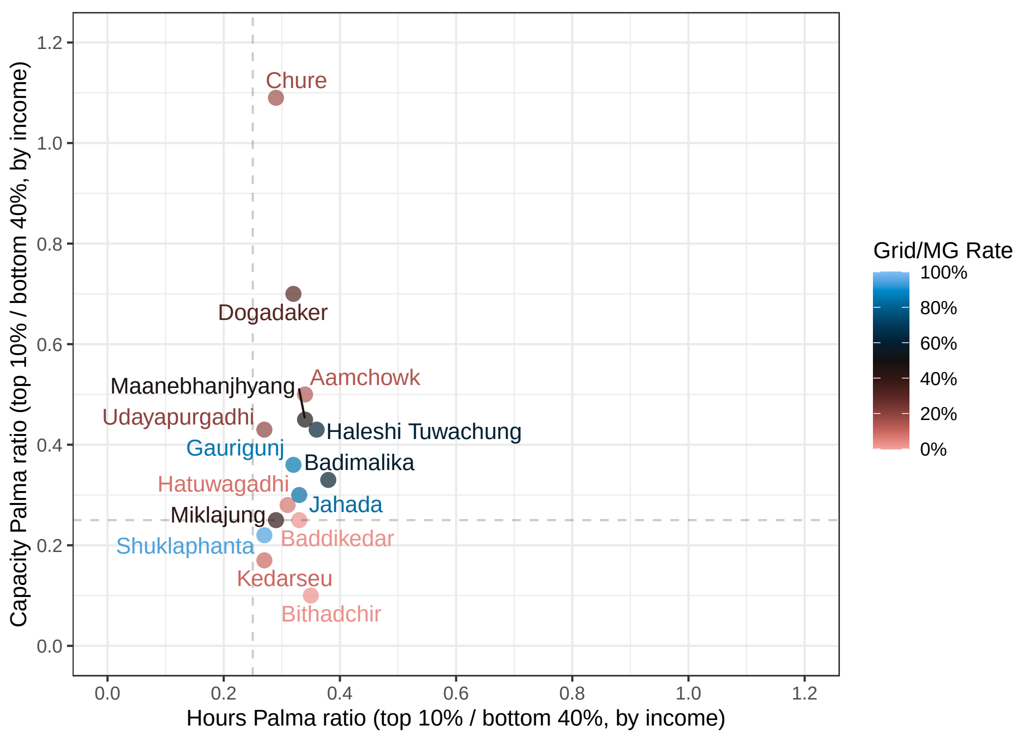

Figure 3.5: Main results, Nepal survey dataset (N = 5,969), within- and across-municipality wealth-related inequities in multi-dimensional electricity supply.

Figure 3.6 uses the same Palma ratio extension to describe wealth-related clean cookstove access inequities across all municipalities. The shapes on the figure describe the Palma ratio extension for the prevalence of each stove type between the top 10% over the bottom 40% of the population by wealth in that municipality. Higher values on the x-axis indicate that the wealthier 10% more often own this form of stove than the bottom 40%. A value of 0.25 as shown by the dashed line indicates a somewhat egalitarian distribution at the aggregate level. Once again, the diverging colour gradient is used to visually evaluate the relationship between improved cooking access across the municipality (BLEN and ICS stoves), with the Palma ratio distributional inequities. ICS and LPG are used interchangeably across the municipalities for the reason that LPG is simply not available in many rural areas[11]. Here it is immediately evident that municipalities exhibit clear wealth-related inequities in terms of the households that are afforded access to either ICS and LPG. Inequities are more severe than those with respect to electricity supply attributes, indicating an urgent need for pro-poor policy reform to bridge these gaps. Considering the diverging colour gradient, a parabolic relationship between wealth-related access inequities and municipal ICS/BLEN penetration is not observed, though the caveat that this is not a representative sample of rural municipalities continues to stand.

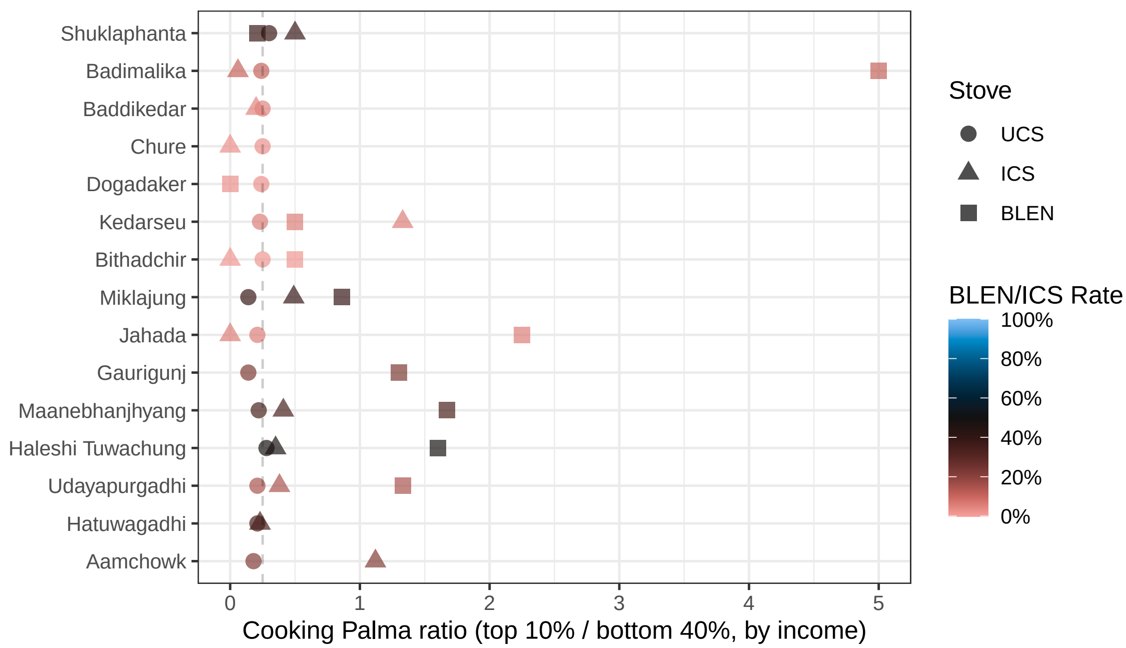

Figure 3.6: Main results: Nepal survey dataset (N = 5,969), within- and across-municipality wealth-related inequities in access to clean cooking.

Finally, Figure 3.7 describes wealth-related inequities energy service access across all municipalities. The same Palma ratio extension approach as that described for clean cooking access is used here. The shapes determine the relative access of the

[11]While ICS are not considered a clean cookstove in this work more broadly, the contextually reality of cooking fuel usage and broader levels of poverty in rural Nepal means that ICS have been extensively distributed in rural areas for their health and fuel consumption benefits over three-stone fire use.

top 10% to the bottom 40% for each energy service group. It is encouraging to see that access to the most basic energy services, namely lighting and communications, is broadly equitable across all rural municipalities, with the notable exception of Haleshi Tuwachung, where a poor minority remains without even these basic services. Contrasting the severity of inequities here with those described in terms of supply attributes above sheds light on the disconnect between the electricity supply provided and the ability for households to translate this into useful energy services that improve their wellbeing. Wealth appears to remain a key modifier of not only equitable electricity supply but more sharply in terms of the functionings households derive once they are afforded access to reliable supply.

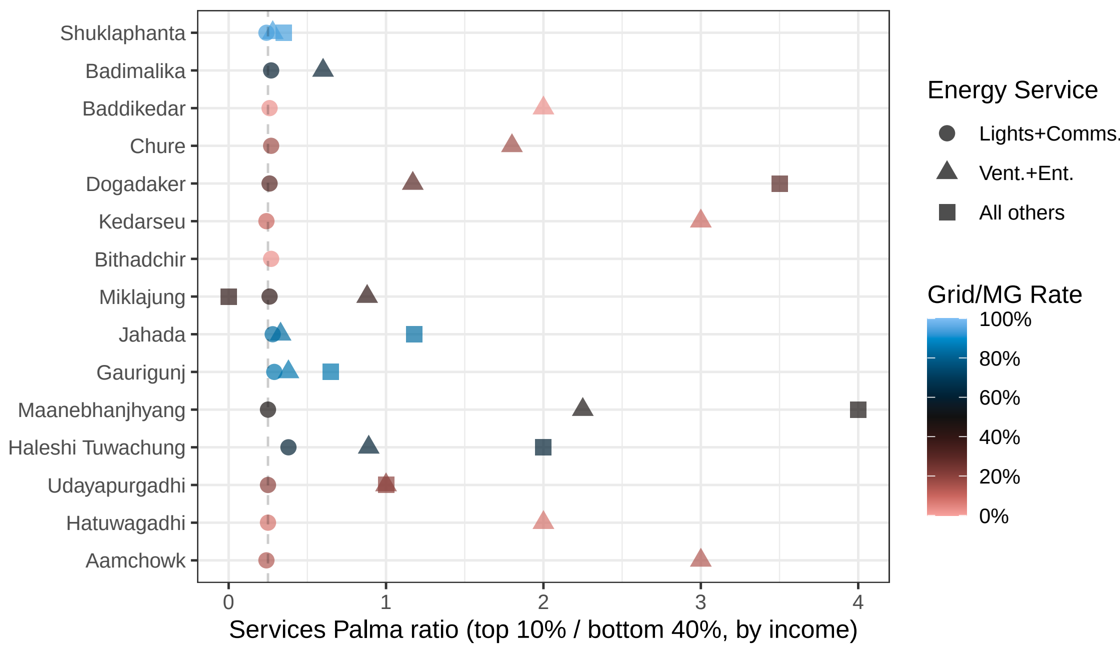

Figure 3.7: Main results, Nepal survey dataset (N = 5,969), within- and across-municipality wealth-related inequities in access to energy services.

3.3.3 Mapping energy supply inequities

Thus far the work in this section has focussed on evaluating recognition justice aspects in terms of capturing and discussing wealth-related inequities across the sampled rural municipalities. Municipal energy supply planning is necessarily a geographic challenge, however, and requires a better understanding of the distributional inequities that need to be addressed. The work here attempts to fill this knowledge gap through spatial interpolation of the efficient representative sample of household surveys. This is limited to describe inequities in access to either the national grid or a local hydropower minigrid across six of the sampled rural municipalities. In the interest of this narrative summary, the discussion of the mechanical aspects of this work is kept brief here. Paper 4 and its appendices describe both the motivation and approach applied here in far greater detail.

The spatial interpolation of household survey data follows a two step process. First, this requires the definition of settlement clusters in a context with limited up to date administrative data describing settlement locations and extents. This is solved using an unsupervised machine learning approach known as density-based clustering, described to some extent in Chapter 1. Second, this requires the linkage of household survey outcomes with spatial and remotely sensed covariates available for the entire municipality. This is attempted using another unsupervised machine learning approach known as gradient-boosting, which is an ensemble prediction approach and once again discussed in Chapter 1. In essence, the geocoded household survey data is linked with existing secondary spatial datasets using machine learning methods to develop a predictive model which describes likelihoods of grid and minigrid connection in population clusters across the entire municipality, including areas that were not enumerated. Functionally, both geocoded survey and secondary spatial datasets are aggregated using the H3 hierarchical index, providing a uniform hexagonal grid across the municipality. The modelling is conducted at this aggregated level and the resulting predictions are then projected on to the population clusters. The limitations of such a modelling exercise are discussed at length in Paper 4, along with a critical evaluation of the predictive accuracy at both the municipal level and also with respect to predictions at the H3 spatial index level.

The resulting predictions of the distributional inequities for each population cluster are reproduced in Figure 3.8. The existing national grid substation and hydropower minigrid locations are shown with red and blue points respectively. Household connection likelihoods to the respective infrastructures within each population cluster are shown by the colour gradients. The modelled dataset and corresponding visualisation provide an indication of the distributional inequities in the likelihood of household grid or minigrid connection including in communities that were not enumerated. From a justice perspective, understanding *where* supply inequities exist is essential to more equitable energy access planning going forward. This includes both areas which lack infrastructure as well as areas where household take-up is low. This is typically quite challenging given the complete lack of spatially representative electricity access data in many regions with infrastructure deficits (see for example Falchetta, Pachauri, Parkinson, & Byers (2019)). Moreover, the downstream implementation of electrification policies, i.e. at the last mile, often features limited data collection activities such that the location of the infrastructure is not recorded. Providing an unbiased and transparent estimate of the actual likelihood of household access to infrastructure in every community is an important step towards equitable progress in municipal energy infrastructure provision for all constituents.

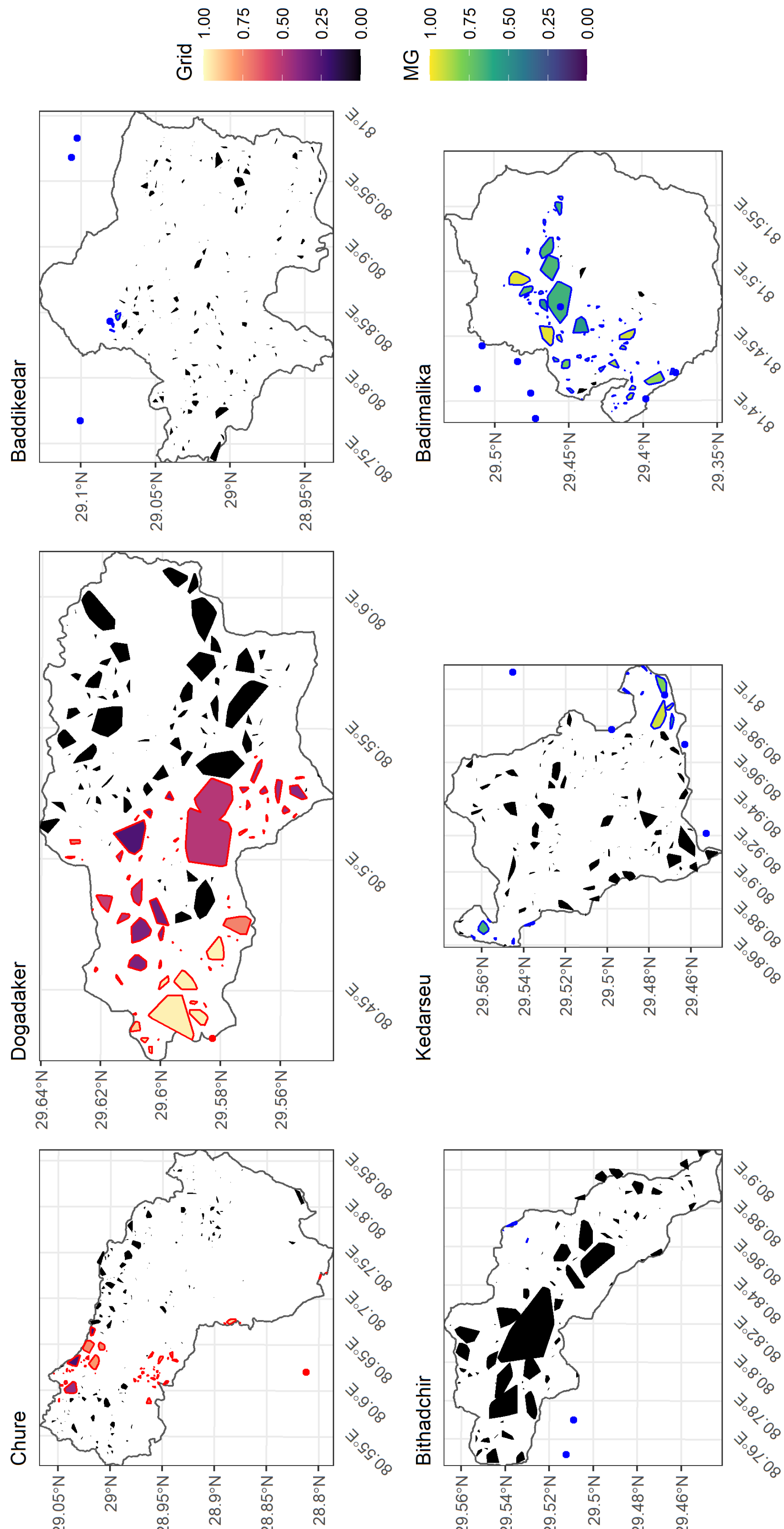

Figure 3.8: Main results: Nepal survey dataset, distributional inequities in access to modern energy infrastructure across selected municipalities.

Chapter 4

Aligning Measures with Capabilities

4.1 An alternative framework for measuring progress towards SDG 7.1

The work thus far has argued for moving beyond binary energy access measurement and theoretically and empirically explored the strengths and weaknesses of applying the MTF as a tool for this. The results of these efforts provide some guidance as to the effective implementation of a multi-dimensional measure for capturing energy access and related capabilities.

Firstly, the distinct attributes of the MTF should be considered as irreducible for the purposes of benchmarking and goal setting. The results indicate that the usefulness of this framework essentially suffers when attributes are aggregated using the least-performing approach in common practice currently. This is due to the observable heterogeneity in the perceived importance of distinct attributes by households and the lack of a sound theoretical basis for their aggregation.

Secondly, both the supply and use of energy should be measured as only the latter actually translates to the well-being benefits energy access unlocks. The results indicate that a focus on supply, even if multi-dimensional in nature, ignores other limitations faced by households and small businesses hindering its effective use. Energy poverty and wealth inequities more broadly are inherently linked, not just in terms of unequal distribution of supply, but also in the unequal access to appliances necessary to achieve a decent living standard.

A way forward was hinted at in Chapter 2, describing a separation of the MTF for either national-level or global-level measurement and tracking. This is now pursued more concretely, building on the work of Pachauri & Rao (2020) to propose an alternative framework for measuring progress towards SDG 7.1[1]. The original AF drew quite concretely from the Decent Living Standards and justice-based approaches towards describing a method for measuring multi-dimensional electricity supply and

[1] The work of Pachauri & Rao (2020) is the first implementation of an alternative framework and provides important theoretical arguments for this approach that supplement the discussion here.

access and requisite services. This was intended to tackle some of the criticisms of the MTF also discussed in Chapter 2 and propose a more pragmatic approach that could still capture heterogeneity at lower income levels. The intention with the new work presented here is to build on the original AF and propose a globally applicable set of indicators that more accurately reflect the original SDG Target 7.1 wording for both electricity and cooking access, which is: *'By 2030, ensure universal access to affordable, reliable and modern energy services'* (UN, 2015).

SDG Target 7.1 is quite clear in its wording. The three considerations are: affordability, reliability and access to modern energy services. These are embedded in the notion of universal access. That is, all households should achieve each of these aspects[2]. This must be balanced against the complexity this entails and the usefulness of a framework for cross-country comparison. With this in mind, the AF was developed as shown in Table 4.1.

Table 4.1: The alternative framework for measuring progress towards SDG 7.1, source: Pelz, Pachauri, & Rao (2021)

Goal	Attribute	Description
SDG 7.1.1	Affordability	Electricity costs <5% of median quintile expenditures
	Reliability	Electricity available >16 hours per day
	Services	Access to at least decent energy services
SDG 7.1.2	Affordability	Fuel costs <5% of median quintile expenditures
	Reliability	BLEN fuels available for 10 months of the year
	Services	BLEN stoves used for >80% of daily cooking time

Affordadability

For both electrical energy services and clean cooking access, the AF sets a threshold limiting expenditure on each of these to 5% of annual household expenditures. This reflects the higher tiers of both the MTF and the original AF. The median annual expenditures within the income or expenditure quintile a household belongs to are used as the denominator here. While this has its limitations, the use of actual energy expenditures[3] and quintile expenditures provides a naive approximation of the affordability threshold for households at the lower tail of the income distribution, including those with suppressed expenditures due to the trade off with manual drudgery. Nevertheless, this remains a weak indicator that must be improved in the future. For

[2]The satisfaction of these must be universal from the language of basic needs theory and the Decent Living Standards. The selected thresholds must therefore be relevant for all households as far as is possible.

[3]The MTF uses a nominal bucket of 1kWh per day of 365 days and the average grid tariff to determine the numerator. This may over or under-estimate consumption in rural and urban areas respectively insofar as necessary for achieving a decent living standard. The use of actual expenditures may be biased in the other direction, as current expenditures of rural households may be suppressed due to wealth constraints limiting appliance purchase.

households with both access to electricity and clean cooking fuels, the sum of expenditures on electricity and cooking fuels is used as the numerator and it is assessed as to whether this is below 10% of the median quintile annual expenditures.

Reliability

Reliability is considered separately for electricity and clean cooking. For electricity, a minimum threshold for supply reliability is set at 16 hours of usable electricity supply each day. This reflects the highest tier within the original AF and is proposed to reflect the minimum level of supply to enable the enjoyment of a minimum set of appliances discussed in the next section. While the negative effects of unscheduled outages and limited capacity are acknowledged, the main limiting factor for the majority of the regions with weak energy infrastructure remains the typical hours of supply provided on a daily basis[4].

Modern energy services

This final aspect of the AF sets it clearly apart from the MTF and current indicators for SDG 7.1. This is also the aspect with the most severe limitations and should be considered a provocation arguing for the inclusion of the use of energy services into future measurement frameworks. For electricity, modern energy services are considered as access to lighting, phone charging and either TV, fridge or space cooling / heating. This basket of appliances is aligned with the material needs under the Decent Living Standards. Nevertheless, the use of an *or* operator is an intentional element given the intended global nature of the framework and limited understanding as to the definition of indicators for universal satisfiers corresponding to these material needs. For cooking the AF captures the relative time spent using Biogas, Liquid Petroleum Gas, Electricity or Natural Gas (BLEN) cookstoves, and sets a threshold of at least 80% of total daily cooking time. Relative time-use is proposed rather than relative fuel consumption as a pragmatic solution to two problems. First, the widespread occurrence of fuel and stove 'stacking'[5] and the challenge of homogenising heterogeneous measurement units and fuel calorific values across diverse country contexts. The underlying logic for this simplification is that more time spent using biomass stoves relative to BLEN stoves will lead to higher biomass fuel consumption and higher exposure to particulate matter.

4.1.1 Applying the alternative framework

To what extent do the current indicators used to measure progress towards SDG 7.1 reflect the wording of the targets? This question is explored through a comparative visualisation of national aggregates for current SDG 7.1 indicators and AF attributes using representative survey data from ten countries gathered under the World Bank

[4]This is explored in further detail in Chapter 3 and Paper 2 and 4.

[5]This refers to the use of multiple fuels and stoves interchangeably as is common practice in resource constrained poorer settings.

ESMAP Multi-Tier Framework For Measuring Energy Access Survey[6]. The results are shown in Figures 4.1 and 4.2. These figures describe the share of the population considered to achieve SDG 7.1.1 (electricity) and SDG 7.1.2 (clean cooking) as per the current indicators. This is shown by the wider grey bars and their corresponding percentage as shares of the population. The share of these households that also achieve each of the three AF attributes are inset and shown as coloured bars with corresponding percentages as the share of SDG 7.1 households.

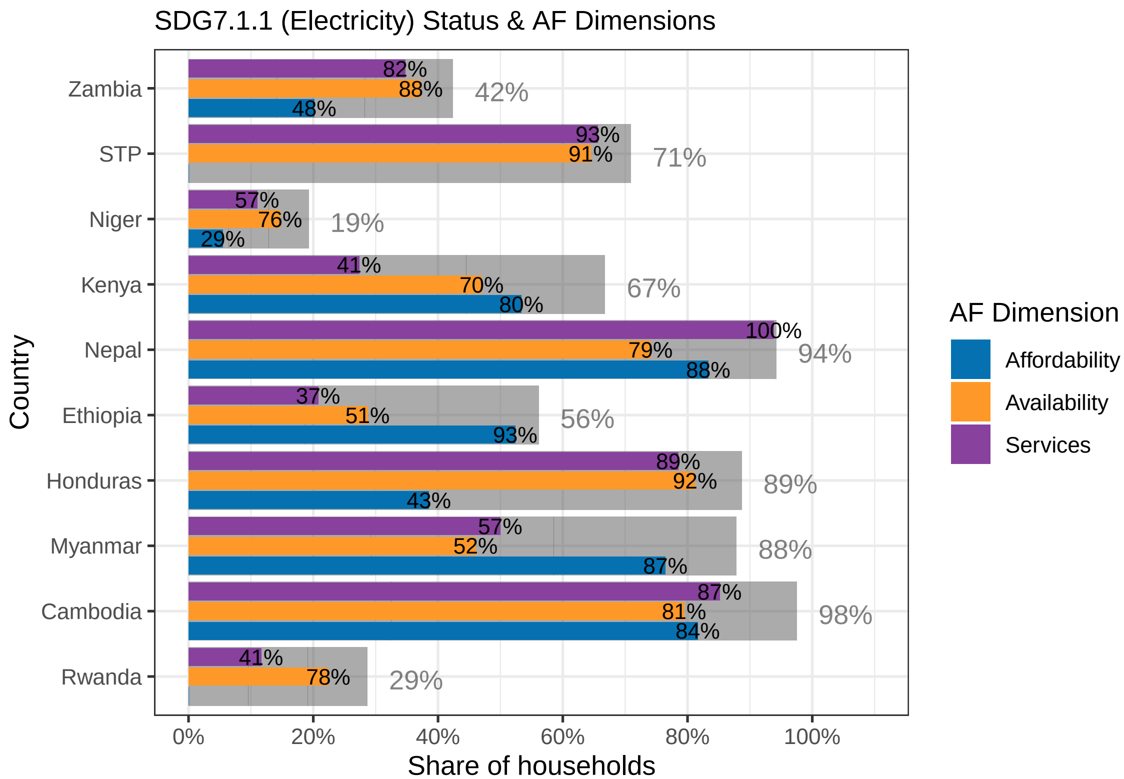

Figure 4.1: Summary statistics: MTF dataset - current SDG 7.1.1 indicator aggregates (grey) and corresponding AF aggregates (inset), source: Pelz, Pachauri, & Rao (2021)

If the SDG Target 7.1 indicators reflected the target wording, that is affordable[7], reliable and modern energy services, we should find that at or close to 100% of households considered served by the current indicators also achieve each AF dimension. This is clearly not the case, with severe deficits across both electricity and clean cooking AF attributes in each of the 10 countries where data was available. It is clear, that the thresholds set for the AF attributes will have significant bearing on this visualisation. The intent is not to explicitly define what each of these attributes

[6]Further detail on the sampling approach and specific sources for each of these country datasets is provided in Paper 5.

[7]It should be noted that household expenditure data was not gathered in Rwanda or São Tomé and Príncipe (STP) and is therefore missing in this analysis.

of energy access should be. Rather, the intent is to show that by the measures defined under the AF (based on the Decent Living Standards), there is a gap between the current indicators and the intention of the SDG Target 7.1 wording. Reflecting on the deficits under SDG Target 7.1.1 (electricity), it would appear that household utilisation of decent energy services varies most across the countries surveyed. Only 37% of SDG Target 7.1.1 households in Ethiopia, 41% in Rwanda and Kenya and 57% in Myanmar and Niger have access decent energy services. This contrasts with 100% of households in Nepal and over 80% of households in Cambodia, Honduras, Zambia and STP.

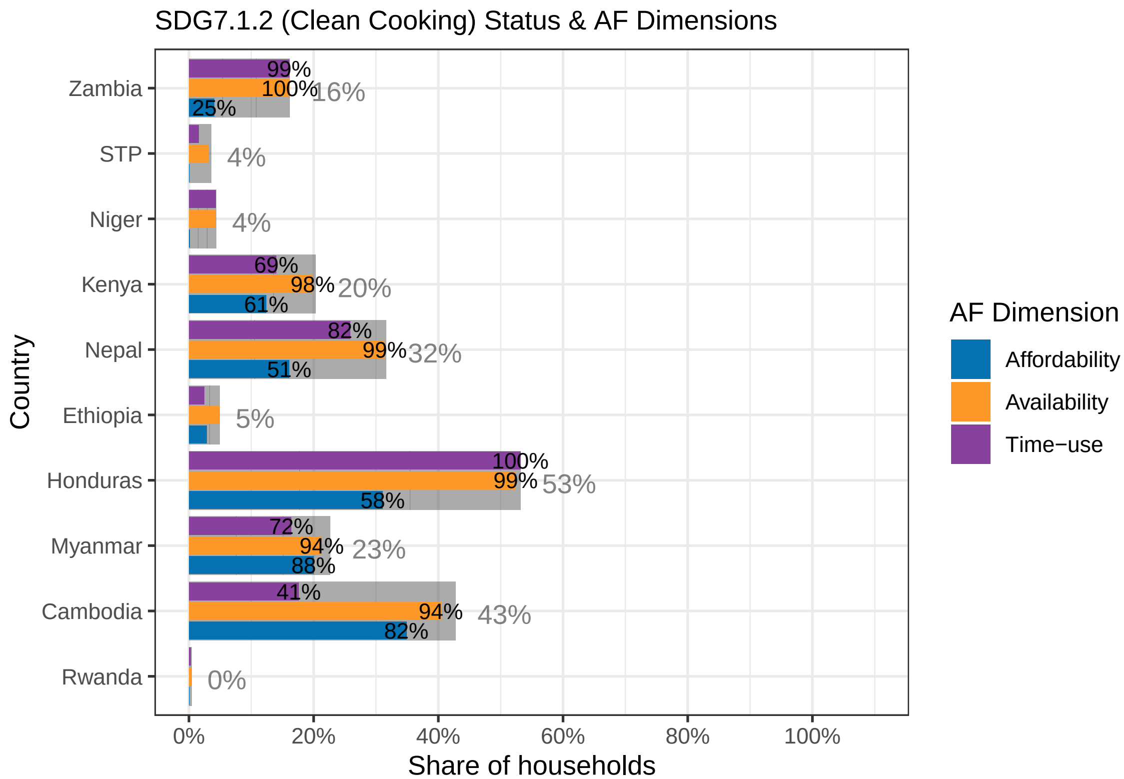

Figure 4.2: Summary statistics: MTF dataset - current SDG 7.1.2 indicator aggregates (grey) and corresponding AF aggregates (inset), source: Pelz, Pachauri, & Rao (2021)

Deficits in decent supply reliability are less severe, but also quite variable across surveyed countries. Approximately half of SDG 7.1.1 households in Ethiopia and Myanmar receive electricity for at least 16 hours per day. This rises to at least 90% of SDG 7.1.1 households in STP and Honduras. Finally, supply affordability is the most severe constraint in any one country, with only 29% of SDG 7.1.1 households in Niger spending less than 5% of the median quintile annual household expenditures on electricity.

The deficit in affordable supply is even more noticeable among SDG 7.1.2 (clean cooking) households. Only 25% (Zambia) of SDG 7.1.2 households allocate less than 5% of the median quintile annual expenditures on cooking fuels. It is also evident that the continued use of solid-fuel cookstoves despite stating primary reliance on a BLEN stove is widespread, with only 41% of households in Cambodia using their BLEN stove(s) for at least 80% of typical daily cooking time. This aggregate reveals an inarguably severe weakness in the current SDG 7.1.2 indicator - households stating that they own a clean cookstove are not necessarily using this, substituting instead a solid fuel cookstove for a non-negligible share of their daily cooking needs. Fuel availability does not appear to be a major constraint in any of the countries surveyed among households considered to have clean cooking access according to the current SDG 7.1.2 indicator, with the vast majority of households having access to clean cooking fuels for at least 10 months of the year.

It is evident from these visualisations that many households that have access to either electricity or clean cookstoves continue to face barriers to their full utilisation and associated improvements to household wellbeing. This raises a question - is there a systematic association across this group of under-served households?

4.1.2 Unmasking inequities

Are the observed deficits across AF attributes associated with household wealth? The final question here is whether the observed deficits in reliable, affordable access to modern energy services among SDG 7.1 households are inequitably distributed. Essentially, do the current indicators for SDG 7.1 mask wealth-related inequities in access to affordable, reliable and modern energy services among households that are considered 'served?' This is first explored using a descriptive visualisation of aggregate access rates and corresponding AF attributes by wealth quintile, shown in Figures 4.3 and 4.4. The black data points also represented by circles show the share of population within each expenditure quintile satisfying the current SDG 7.1 indicators. The remaining data points represented by other shapes reflect the share of households also satisfying each AF attribute. Across countries with high levels of access as per SDG 7.1, such as Cambodia, Myanmar, Honduras and Nepal, a general trend indicating a convergence of some AF attribute rates and SG 7.1 indicator access rates with expenditure quintiles seems to appear. This is, however, not clear across all AF attributes and differs between clean cooking and electricity access. Moreover, this relationship is less evident and somewhat mixed for countries with very low overall rates of access.

Linear regression analysis is used once again to adjust for confounding in describing this relationship. This analysis is restricted to those households considered served under the current SDG 7.1 indicators (those with either access to electricity and/or a clean cookstove). A linear probability model is applied using Country $\times$ Rural $\times$ Administrative Level 2 fixed effects. This compares the differences in the likelihood to achieve each AF attribute threshold across wealth quintiles within these groups. The results of this analysis are shown in Tables 4.2 and 4.3. The coefficients can be interpreted as *SDG 7.1 households in expenditure quintile X have a* $\beta \times 100$ *percentage-point higher likelihood to achieve each AF attribute threshold relative to those in the lowest quintile.* A correlation plot is provided in Figure A.3 of Appendix Section A.

The null hypothesis here is that the likelihood to achieve each AF attributes among

SDG 7.1 households should be evenly distributed across wealth quintiles within the same urban or rural regions of a second-level administrative area in a country. That is, there should be no difference in the likelihood to achieve the AF threshold conditional on wealth quintile within these groups. There are few reasons for differences in supply quality within these groups, other than a geographic preference for urban centres which may also correspond to higher wealth households, or a general bias towards neighbourhoods with higher wealth households. Nevertheless, this is not a fully identified model and should be viewed as a descriptive analysis, not one describing any causal relationships. Notwithstanding these caveats, differences across expenditure quintiles here would point towards the existence of masked inequities among households that are considered equally served under the current SDG 7.1 indicators.

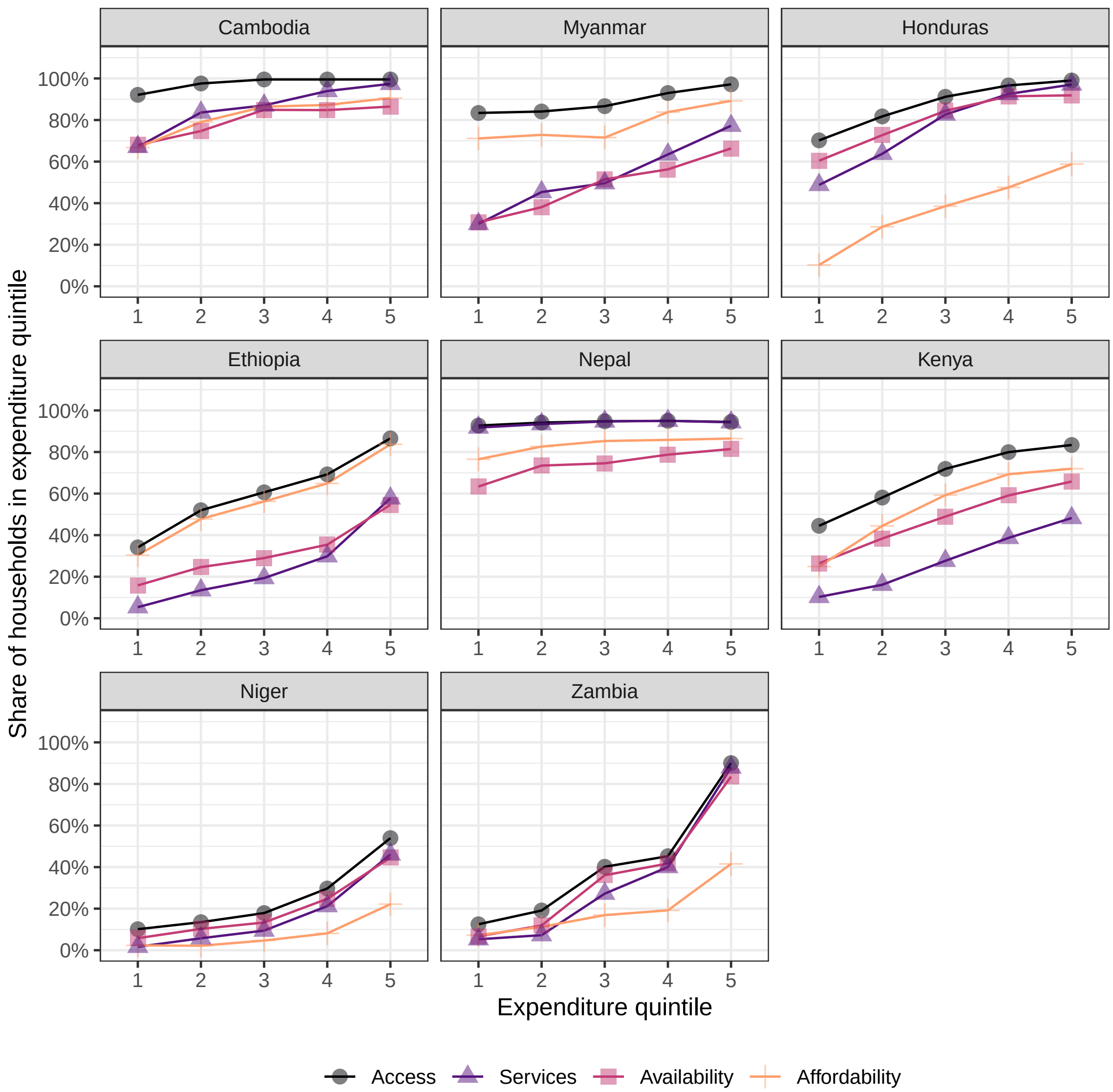

Figure 4.3: Summary statistics: MTF dataset - SDG7.1.1 (Electricity) Status and AF Dimensions by Expenditure Quintile.

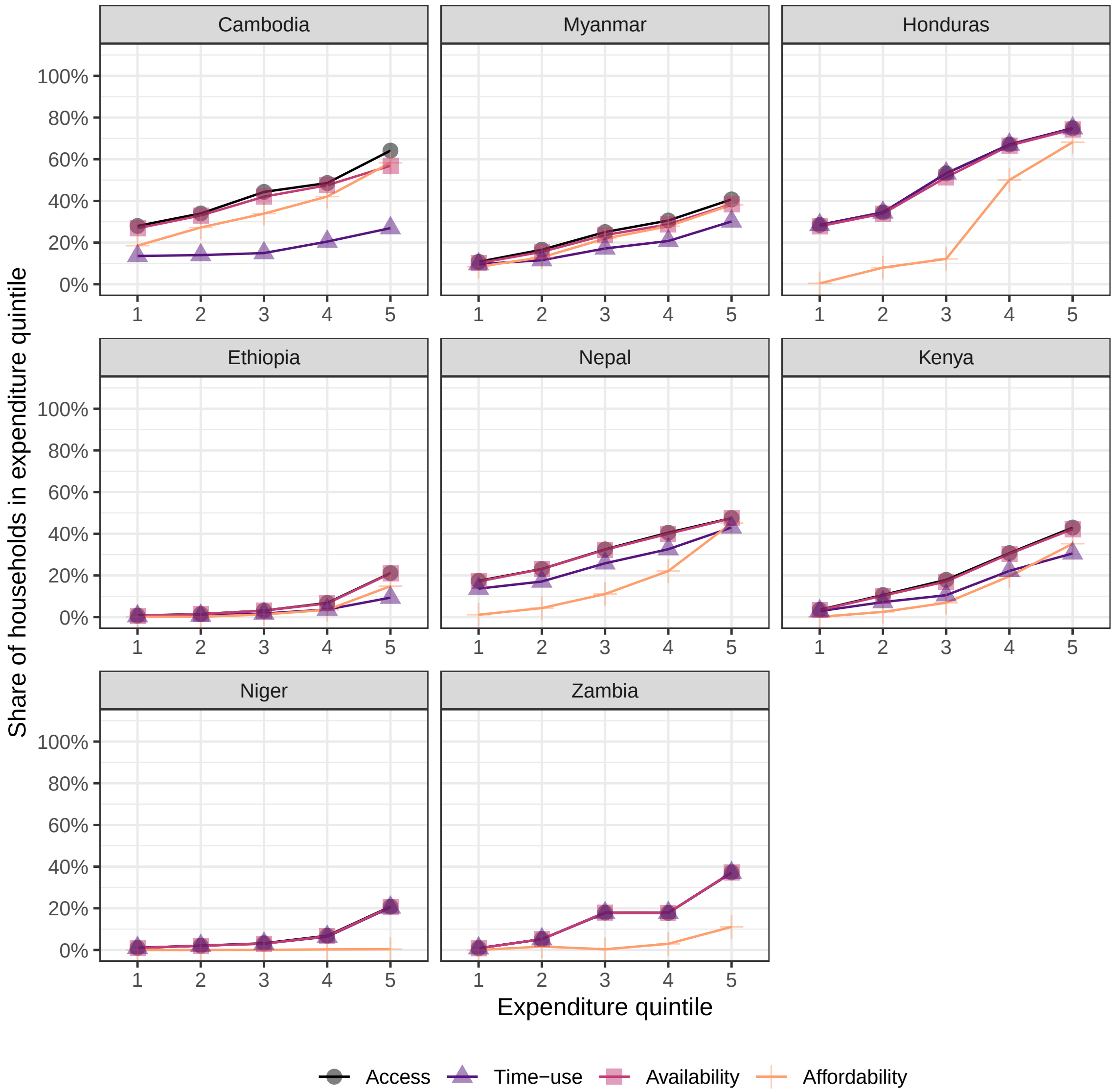

Figure 4.4: Summary statistics: MTF dataset - SDG7.1.2 (Clean cooking) Status and AF Dimensions by Expenditure Quintile.

Among SDG 7.1.1 (electricity) households, the regression coefficients and standard errors indicate that the null hypothesis can be broadly rejected. It does appear that wealthier households also tend to have more affordable, reliable and modern access to electrical energy services relative to poorer households. This is indicative of systematic inequities hidden behind aggregate indicators used to measure progress towards SDG 7.1, a trend that must be rectified. In contrast, the findings are less clear among SDG 7.1.2 (clean cooking) households, most likely due to the low levels of access overall. Here, access to affordable clean cooking fuel supply appears to be strongly correlated with wealth, but its reliability and use (as a share of daily cooking time) are not. The evidence for systematic wealth inequities is supported by the typical lack of corrective tariffs for clean fuel access among the poor. That is, there are limited examples of block-tariffing or ‘lifeline’ tariffs providing a minimum amount of clean cooking fuel to poorer households, relative to those for minimum electricity services.

Although the thresholds set under the AF may be vulnerable to debate, the results are sufficiently sharp to initiate a discussion of revising the existing SDG Target 7.1.1 indicators at the next opportunity. At the same time, while the results are not as conclusive among SDG 7.1.2 households, it remains crucial to consider the inclusion of these attributes into SDG Target 7.1.2 tracking moving forward. Indicators relying solely on the provision of connections to a modern energy source insufficiently control for institutional or governance weaknesses that can result in persistent inequities among the poor and marginalised. This work joins the chorus of recent scholarship arguing the need for more ambitious targets and more detailed data collection activities for guiding progress towards sustainable energy for all.

Table 4.2: Main results: MTF dataset - linking AF attribute satisfaction with household wealth among SDG 7.1.1 households.

Dependent Variables:	Services	Reliability	Affordability
Model:	(1)	(2)	(3)
Variables			
ExpenditureQuintile2	0.074***	0.022	0.080***
	(0.015)	(0.029)	(0.020)
ExpenditureQuintile3	0.105***	0.070***	0.131***
	(0.019)	(0.025)	(0.023)
ExpenditureQuintile4	0.162***	0.084***	0.194***
	(0.019)	(0.028)	(0.024)
ExpenditureQuintile5	0.231***	0.109***	0.278***
	(0.021)	(0.025)	(0.023)
Fixed-effects			
Country-Rural-Admin2	Yes	Yes	Yes
Fit statistics			
Observations	23,896	23,292	18,489
R^2	0.56939	0.56416	0.28376
Within R^2	0.03588	0.01012	0.02870

Clustered (PSU) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

Table 4.3: Main results: MTF dataset - linking AF attribute satisfaction with household wealth among SDG 7.1.2 households.

Dependent Variables:	Time-use	Reliability	Affordability
Model:	(1)	(2)	(3)
Variables			
ExpenditureQuintile2	-0.072	0.003	0.186***
	(0.046)	(0.024)	(0.042)
ExpenditureQuintile3	-0.102**	0.015	0.228***
	(0.040)	(0.024)	(0.038)
ExpenditureQuintile4	-0.084**	0.016	0.519***
	(0.036)	(0.020)	(0.033)
ExpenditureQuintile5	-0.062*	0.014	0.723***
	(0.035)	(0.020)	(0.032)
Fixed-effects			
Country-Rural-Admin2	Yes	Yes	Yes
Fit statistics			
Observations	8,485	8,631	6,879
R^2	0.40569	0.15119	0.41888
Within R^2	0.01078	1.37×10^{-5}	0.16189

Clustered (PSU) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

4.2 A case study of energy access inequities in rural northern India

The final section of this chapter explores the importance of sub-national multi-dimensional energy access measurement through a case study in rural northern India. This case study is placed here as it offers the in-country motivation for measuring multi-dimensional supply attributes as a complement to the global cross-country case shown earlier. This work is conducted using the ACCESS dataset once again, which describes changes in access and use of energy across rural areas of six contiguous states in northern India between 2015 and 2018. 8,563 households from 714 villages were surveyed in Wave 1 (2015), and 9,071 households from 756 villages were surveyed in Wave 2 (2018).

4.2.1 Energy access trends among the marginalised

This section explores whether changes in energy access, both in terms of connections but also in terms of multi-dimensional supply attributes differ between historically marginalised scheduled caste or tribe (SC/ST) households[8] and all others. We know from historical data that grid electricity and LPG access rates have been low across rural northern India. Moreover, we know that household access to grid electricity and LPG for SC and ST communities in rural areas is lower still, relative to all others. This is discussed at length in Paper 6, including the analysis of National Sample Survey Office reports from the Ministry of Statistics and Programme Implementation of the Government of India as well as a review of the pertinent literature.

Over the last decade, significant progress has been made following a series of progressive pro-poor energy access policies that first targeted village-level electrification and more recently household-level electrification. Household LPG connections, which refers to household official registration enabling purchase of LPG cylinders, have also been the target of recent policy reform. An excellent summary of the history of rural electrification policies in India is provided by Palit & Bandyopadhyay (2017) and discussed in more detail, alongside LPG-related policies, in Paper 6. The aggregate improvements described by the official statistics lead to two questions. First, considering the historical caste-based inequities in energy access, how equitable have these programs been? Secondly, how do the attributes of the supply provided compare and how did these change over time?

These questions are considered using two approaches. First, changes in energy access and supply attributes across the entire pooled ACCESS dataset are considered. This includes all households surveyed in both survey waves. The outcomes thus include the supply provided to those households that gained (or lost) access between the two survey waves. This approach is referred to below as *Differences in access*

[8] An SC/ST household belongs to an endogamous social group defined by the complex hierarchical caste system in India. This deserves a lengthy and nuanced discussion beyond the scope of the summary presented here. Suggested further readings on the historical roots of these inequities are provided in Paper 6.

Table 4.4: Summary statistics: ACCESS dataset (N = 17,634) - Representative shares of SC / ST households in rural areas of the six states surveyed.

State	SC_2015	SC_2018	ST_2015	ST_2018
Uttar Pradesh	21.1%	21.9%	0.9%	1.0%
Bihar	15.4%	16.5%	2.4%	2.3%
West Bengal	21.9%	22.4%	14.8%	14.9%
Jharkhand	9.9%	12.1%	23.1%	22.8%
Odisha	20.3%	22.3%	30.3%	27.0%
Madhya Pradesh	16.9%	16.7%	15.3%	14.9%

and supply trends across the full dataset and uses the full representative sample-weighted ACCESS dataset (N = 17,634). Second, changes in energy supply attributes for a balanced panel subset of grid-connected and LPG-connected households are separately considered. The outcomes separately capture changes in supply attributes only for those households that already had electricity or LPG in 2015 and maintained this connection in 2018. The outcomes thus reflect the change in supply attributes only between those that had access in 2015. This approach is referred to below as *Differences in supply trends for SDG 7.1 households* and uses a balanced but un-weighted panel subset of grid-connected households (N = 10,556) and a balanced but un-weighted panel subset of LPG-connected households (N = 3,078). The outcome[9] variables are:

- Grid Access (SDG 7.1.1), indicating grid connection.
- AF Reliability, indicating grid connection and >=16 hours supply per day.
- LPG Access (SDG 7.1.2), indicating LPG connection (cylinder-based).
- LPG Home Delivery, indicating LPG connection and home cylinder delivery.

While these outcomes are not complete in terms of multi-dimensional supply attributes that could be considered, they provide sufficient insight into the differences in supply attributes for the purposes of the research question here. The analysis is conducted by pooling all six contiguous states. The distribution of household caste by state for the full access dataset is provided in Table 4.4. A more complete analysis of all supply attributes as well as state-level analysis is provided in Paper 6. This is helpful to understand the state-level effects of differences in SC/ST compositions across states and reflect on mechanisms for the inequities found.

[9]Here the outcomes are coded such that supply attributes for households households without a connection are set to zero.

4.2.2 Differences in access and supply trends across the full dataset

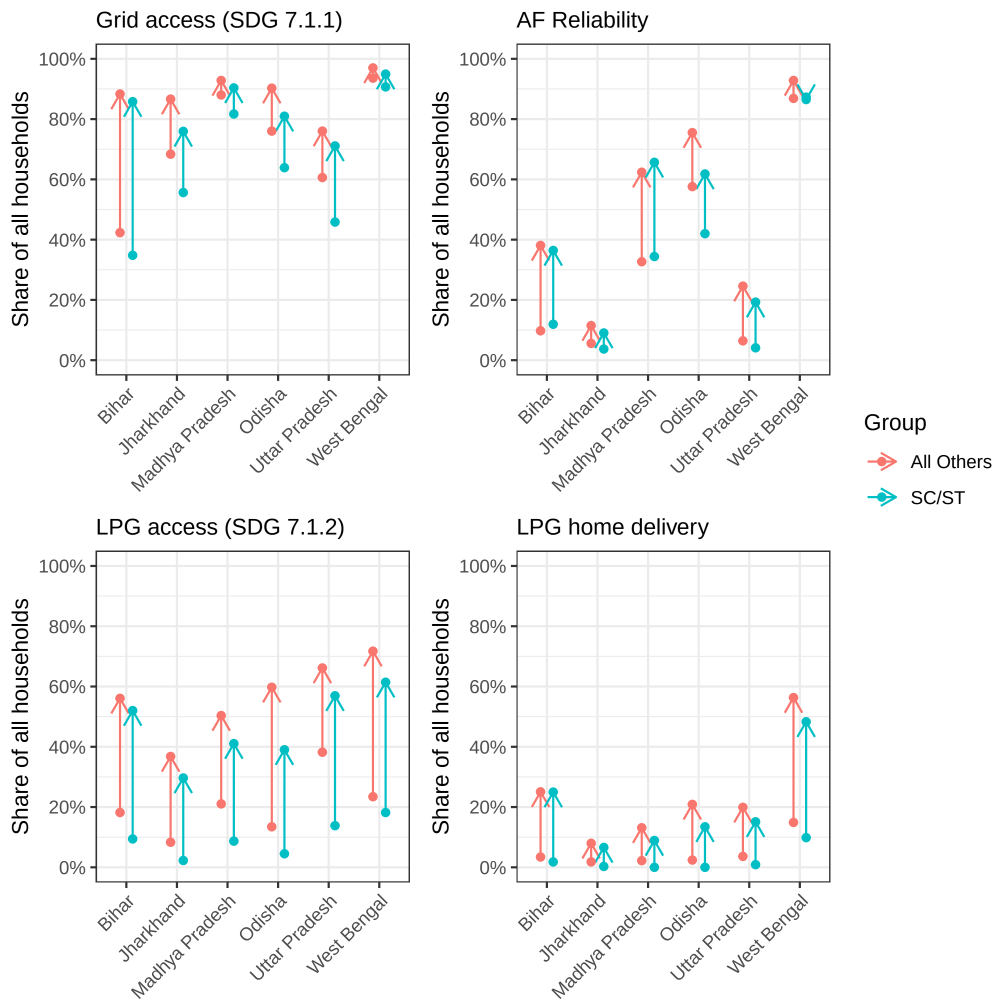

Figure 4.5: Summary statistics: ACCESS dataset (N = 17,634) - representative sample-weighted change in energy access means from 2015-2018 for SCST and All Other households.

Figure 4.5 provides a visualisation of the outcomes aggregated by state across the entire ACCESS dataset. The colours reflect the two groups in our analysis and the arrows reflect aggregate changes in outcomes from 2015 to 2018. Considering access to electricity, it appears that SC/ST households had lower rates of electricity access in 2015 across each state, although the reliability of supply appears more mixed and state-dependent. LPG access was lower across the board in 2015 and appears to have improved the most, though once again the convenience of supply appears more mixed, with some states, e.g. West Bengal far outperforming the others. These figures provide context to the subsequent regression analysis, presented in Tables 4.5 and 4.6.

A linear probability model with household fixed effects is used for each of the four binary outcomes. The model contains the interaction term $SC/ST \times 2018$ where SC/ST is a dummy indicating SC/ST status and 2018 is a dummy indicating that the observation is from the second survey wave. This interaction term estimates the difference in the change in SC/ST outcomes relative to All Others between 2015 and 2018. A series of covariates are included that may change within households and influence both the outcome and the interaction term coefficients. These include log of monthly expenditures, household size and whether the household has a Below Poverty Line ration card, indicating extreme poverty. Further detail and justification of the model specification as well as alternative specifications can be found in Paper 6. A correlation plot is provided in Figure A.4 of Appendix Section A, The results

Table 4.5: Main results: ACCESS dataset (N = 17,634) - difference in electricity supply trends from 2015-2018 between SC/ST households and All Others.

Dependent Variables: Model:	Grid connected (1)	AF Reliability (2)
Variables		
2018	0.176***	0.174***
	(0.007)	(0.008)
SC/ST × 2018	-0.008	-0.043***
	(0.013)	(0.015)
Fixed-effects		
Household	Yes	Yes
Fit statistics		
Observations	17,570	17,569
R^2	0.69495	0.75126
Within R^2	0.13608	0.10873

Clustered (Household) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

can be interpreted as follows: β_{2018} reflects the conditional change between 2015 and 2018 for All Other households. $\beta_{SC/ST \times 2018}$ reflects the relative conditional difference in the change in SC/ST outcomes relative to All Others between 2015 and 2018. A discussion of the vulnerabilities of panel data analysis with fixed effects has already been provided in Chapters 1 and 3. Nevertheless, in this case it is important to note that this model specification assumes that the *treatment*[10] occurs at the same time for all households. In this case, the *treatment* is in a sense time itself, as we are

[10]In this case, the *treatment* is time passing and the groups are SC/ST versus All Others. Ideally, we want to estimate differences in outcomes across these groups over time that are explained, and only explained, by their SC/ST status.

interested in conditional differences in improvement to supply between two groups from 2015-2018, rather than ascribing these to specific policy changes. Thus, as this is not a causal difference-in-differences specification, despite its obvious analogies, the concerns presented in the contemporary literature are somewhat less severe, but still relevant. The results show that the null hypothesis that rates of grid connection rates

Table 4.6: Main results: ACESS dataset (N = 17,634) - difference in LPG supply trends from 2015-2018 between SC/ST households and All Others.

Dependent Variables:	LPG connected	LPG home delivery
Model:	(1)	(2)
Variables		
2018	0.346***	0.223***
	(0.009)	(0.008)
SC/ST × 2018	0.043***	-0.004
	(0.016)	(0.014)
Fixed-effects		
Household	Yes	Yes
Fit statistics		
Observations	17,570	17,570
R^2	0.70633	0.63906
Within R^2	0.33022	0.20509

Clustered (Household) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

continued to increase in parallel for both SC/ST and All Other households could not be rejected. In contrast, rates of access to a grid connection providing at least 16 hours of supply were different, with SC/ST household supply improvement falling 4.3 [95% CI 1.3-7.2] percentage points behind All Others. Thus we can learn two things from this table. First, it appears that inequities in access to a grid connection (historically lower among SC/ST groups) remained consistent. The gap did not close in the time period between 2015-2018. Second, it would appear that inequities in supply quality grew slightly. The supply hours provided to All Other households increased more, on average, than SC/ST households between 2015-2018. Conversely, rates of LPG connection improved 4.3 [95% CI 1.2 - 7.4] percentage points more than All Others, however the null hypothesis that access to LPG home delivery improved at the same rate could not be rejected. Looking purely at aggregate connection indicators, it would appear that the gap in access to LPG is reducing. However, inequities in home delivery of LPG, a crucial indicator of continued use, remain.

4.2.3 Differences in supply trends for SDG 7.1 households

Figure 4.6 describes the changes in supply attributes for the balanced panel subset of grid-connected (N = 10,556) and LPG-connected (N = 3,078) households. It is evident that the share of SDG 7.1.1 (grid-connected) households with a reliable grid connection differs strongly across the states, as do the improvement rates. Jharkhand and Uttar Pradesh provide a notable comparison, with two very different levels of success in the improvement of access to reliable electricity supply. Similarly, rates of LPG home delivery among SDG 7.1.2 (lpg-connected) households were quite different across the six states, with West Bengal remaining the leader.

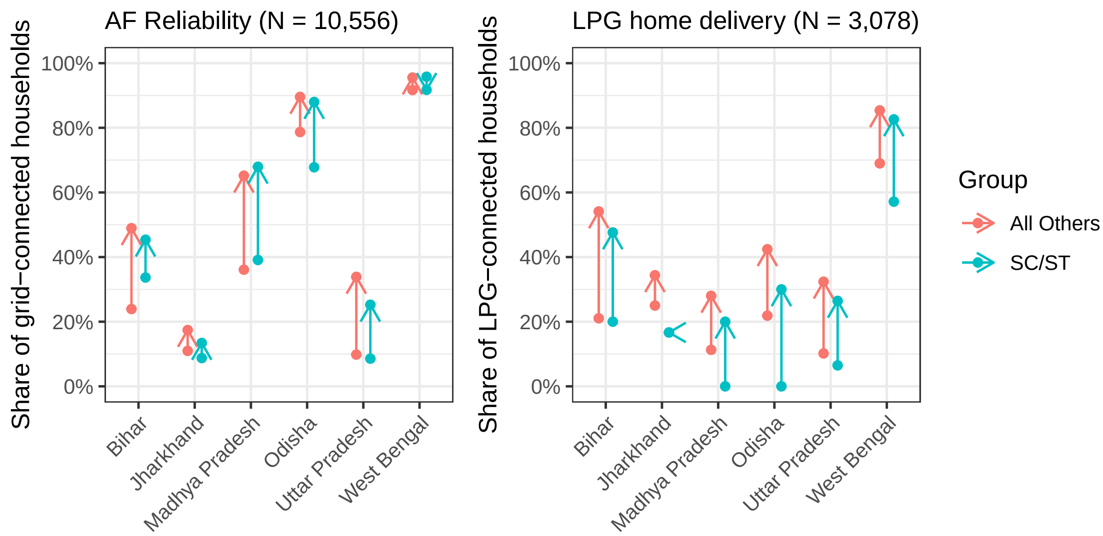

Figure 4.6: Summary statistics: Balanced ACCESS SDG 7.1 panel subsets - change in supply attributes from 2015-2018 for SCST and All Other households.

Table 4.7 provides some insight into the differences in trends somewhat difficult to identify using these figures. The same model specification is used as before, with each model applied to the corresponding panel subset. The results describe the change in supply attributes for the balanced panel subset of SDG 7.1 households. The coefficients for the interaction term indicate that supply reliability improved 7.5 [95% CI 4.2-10.8] percentage points (or 50%) *less* for grid-connected SC/ST households, relative to all other grid-connected households. This underlines the hypothesis that the current policy environment focussed on connections is not providing sufficient incentives and controls for states to improve grid supply quality, especially among marginalised communities. The null hypothesis that LPG home delivery rates increased in parallel could not be rejected, suggesting that while inequities in LPG access are reducing, inequities in persistent use of LPG and reduction in manual drudgery associated with home delivery remain. Measuring progress towards connections evidently not only masks inequities for households recently connected, but also insufficiently captures the reliability of supply for those already with access. This

Table 4.7: Main results: Balanced ACCESS subsets - differences in LPG and grid supply attributes from 2015-2018 between SC/ST households and All Others.

Dependent Variables:	Reliability	LPG home delivery
Model:	(1)	(2)
Variables		
2018	0.156***	0.223***
	(0.009)	(0.018)
SC/ST × 2018	-0.075***	0.009
	(0.017)	(0.048)
Fixed-effects		
Household	Yes	Yes
Fit statistics		
Observations	10,519	3,071
R^2	0.74255	0.69603
Within R^2	0.08296	0.16950

Clustered (Household) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

concludes the narrative summary of empirical work conducted during this research project. It should be noted once again that this reflects a selection of the analysis conducted within the peer-reviewed papers. Moreover, the discussion of results is restricted to that which is relevant for the central narrative of this summary. Each paper includes a detailed discussion of the findings in their local context as well as further methodological and conceptual justification. It is therefore encouraged once again to refer to the papers themselves in reflecting on the specific context in which the results are interpreted and to gain a broader overview of the pertinent literature.

Synthesis

The narrative summary presented here has explored the measurement of energy access and energy poverty, and its role in guiding policies to facilitate universal and equitable energy access. This is based directly and entirely on a set of six distinct peer-reviewed papers that comprise the actual body of work. These are included in full in the appendices to this text. Each individual paper includes far greater methodological detail and discussion of the results in the respective context. Notwithstanding this important caveat, the following synthesis presented here summarises the key contributions of this body of work in the context of this narrative summary.

The work is conducted on the basis of a theoretical foundation defined by the Capabilities Approach, the Decent Living Standards and Energy Justice theory. These justice-based approaches conceptually link household well-being and freedoms with energy services and guide both the development of the research questions as well as the discussion of the results. Guided by this theoretical foundation, the work establishes the status-quo of energy access measurement and critically evaluates this along two lines. First, the inadequacy of binary connection-based indicators for measuring progress towards SDG Target 7.1 is discussed. From a justice perspective, there is a clear mismatch between current connection-based indicators and the wording of SDG Target 7.1: *"ensure universal access to affordable, reliable and modern energy services."*. The current target indicators do not capture reliability or affordability of supply, nor do they address household access to modern energy services. Second, a critical evaluation of contemporary multi-dimensional measures showcases immense progress in our conceptual understanding of energy access measures. However, it also finds rigid assumptions and severe limitations in the design of the leading measurement approach, the Multi-Tier Framework (MTF). The MTF disaggregates energy access across a series of distinct attributes. It then reduces it into an aggregate tier by the lowest performing attribute, assuming all attributes to be equal. The MTF also presents a pragmatic focus on supply, and implicitly ranks appliances by power consumption rather than a theory of basic needs.

Econometric analysis is applied to test these assumptions in the design of the MTF using household survey data collected in northern rural India. The empirical work rejects the aggregation assumption, indicating that distinct attributes of supply are not equally valued by households, at least in the context of rural northern India. The empirical work also shows that a focus on supply can mask inequities in household access to basic energy services. That is the satisfaction of desired energy services, cannot be assumed to occur if supply is provided as this is much more related to wealth constraints than supply constraints in the context studied. To understand whether this is a feature unique to residential energy consumption, the relationship between electricity supply hours and utilisation among micro- and small-enterprises (MSEs) in rural northern India is also tested. The survey data reveals very low levels of electricity consumption among the sampled firms and a linear regression model is unable to statistically link this with grid electricity supply constraints. The results reinforce the need to consider satisfaction of energy services alongside multi-dimensional supply constraints.

These results lead to two central propositions of this work. First, energy supply should be assessed across distinct irreducible attributes until a sound justification for weighted aggregation based on household preferences is established. Second, given that the justice-based approaches argue that the satisfaction of basic needs is the ultimate goal of energy service provision, it is imperative that measures reflect this satisfaction in some form. Measurement of only one side of the supply and consumption equation cannot fully capture inequities in access to reliable, affordable and modern energy services. These propositions inform the fourth piece of work, which describes geographic and wealth-related inequities in energy supply and use across selected rural municipalities in far-western and far-eastern Nepal. This represents the first attempt at improving on the MTF from a justice-based perspective in order to overcome the limitations discussed above. The severe wealth-related inequities observed underline once again that both distinct attributes of supply and satisfaction of basic energy services must be captured in order to inform equitable progress across the full income distribution. An added feature of this piece of work is the application of a transparent and unbiased data collection approach which ensures representation from all segments of the population in a given municipality.

These theoretical arguments and empirical findings are then synthesized to propose an alternative framework (AF) for measuring global progress towards SDG Target 7.1. This is shown once more in Table 4.8 for the purposes of this synthesis. The AF expands on the prior work of co-authors and describes a framework for capturing attributes of supply and utilisation aligned with the material requirements stipulated under the Decent Living Standards.

Table 4.8: The alternative framework for measuring progress towards SDG 7.1, source: Pelz, Pachauri, & Rao (2021)

Goal	Attribute	Description
SDG 7.1.1	Affordability	Electricity costs <5% of median quintile expenditures
	Reliability	Electricity available >16 hours per day
	Services	Access to at least decent energy services
SDG 7.1.2	Affordability	Fuel costs <5% of median quintile expenditures
	Reliability	BLEN fuels available for 10 months of the year
	Services	BLEN stoves used for >80% of daily cooking time

The AF directly follows the propositions described above. First, the AF considers each attribute as distinct and irreducible for the purposes of measurement. Second, the AF captures both supply and usage in one framework. To demonstrate its functional difference to existing measures, the AF is applied to recent household survey data from ten countries and compared against the current indicators for SDG Target 7.1. The results reveal severe deficits in affordable and reliable access to modern energy services among households considered 'served' by the current indicators. Moreover, these deficits appear to be systematically associated with household wealth, such that poorer households considered served under the current SDG Target 7.1 indicators are less likely to have affordable and reliable access to modern energy services. This puts forward a strong empirical case supporting the theoretical concerns raised in the earlier pieces of work with respect to measures for guiding equitable progress towards SDG Target 7.1 for all segments of the population.

Finally, returning once more to the sub-national perspective, a case-study of energy supply provision among marginalised populations in rural northern India demonstrates the importance of multi-dimensional measurement as a control for institutional and governance weaknesses that can reinforce historical socio-cultural inequities as aggregate energy access rates (i.e. connections) improve. The results complicate the rapid progress reported following pro-poor energy policy reform in rural northern India by describing inequities in the associated quality of supply provided, measured as typical hours of supply for electricity and home delivery of LPG for clean cooking. In short, it appears that a focus on connections to modern energy sources is vulnerable to state-level institutional capacity limitations to the detriment of supply quality for marginalised communities. The resulting inequities in supply provision to marginalised populations are entirely masked by aggregate access rates that paint a picture of progress for the population as a whole. The central propositions are thus reinforced by these results - it is crucial that energy access is considered as comprised of distinct irreducible attributes in order to control for institutional weaknesses modifying implementation.

The AF and its applications serve as a clear and direct provocation for further discussion into how SDG Target 7.1 is measured. Notwithstanding limitations in the definition of thresholds across the selected attributes, the AF is arguably the most complete representation of SDG Target 7.1 in indicator form. It is hoped that this sparks discussion as thoughts turn to evaluation of progress along the SDGs as well as the global post-2030 agenda. Such an evolution towards multi-dimensional SDG 7.1 measurement will naturally require the collection of requisite disaggregate data. This reflects the next challenge - standardising multi-dimensional measures and integrating such standard components into ongoing national data collection processes.

In conclusion, this dissertation joins a chorus of recent scholarship arguing for improvement to SDG Target 7.1 indicators and national-level data collection efforts to inform equitable progress towards universal energy access. The theoretical and empirical contributions described here are not without their own limitations, nonetheless it is hoped that the distinct articles influence and contribute to the transition towards a more egalitarian distribution of energy infrastructure and access to energy services necessary to achieve a decent living standard for all.

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The references here refer to the citations in the narrative summary text. References specific to each published paper are provided in the appendices following each paper.

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Appendix A

Supplementary Materials

A collection of supplementary materials to the narrative summary are provided here. Each paper includes its own supplementary materials that provide robustness checks or further analysis as necessary. These are included following each paper in the subsequent appendices.

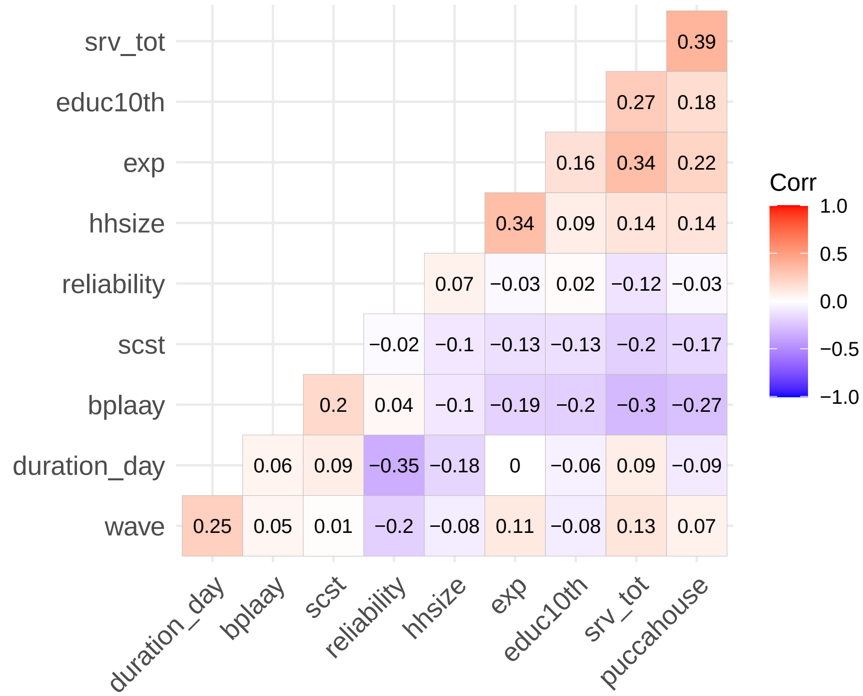

Figure A.1: Chapter 3: ACCESS grid-connected panel subset (N = 10,556) - Pooled correlation plot.

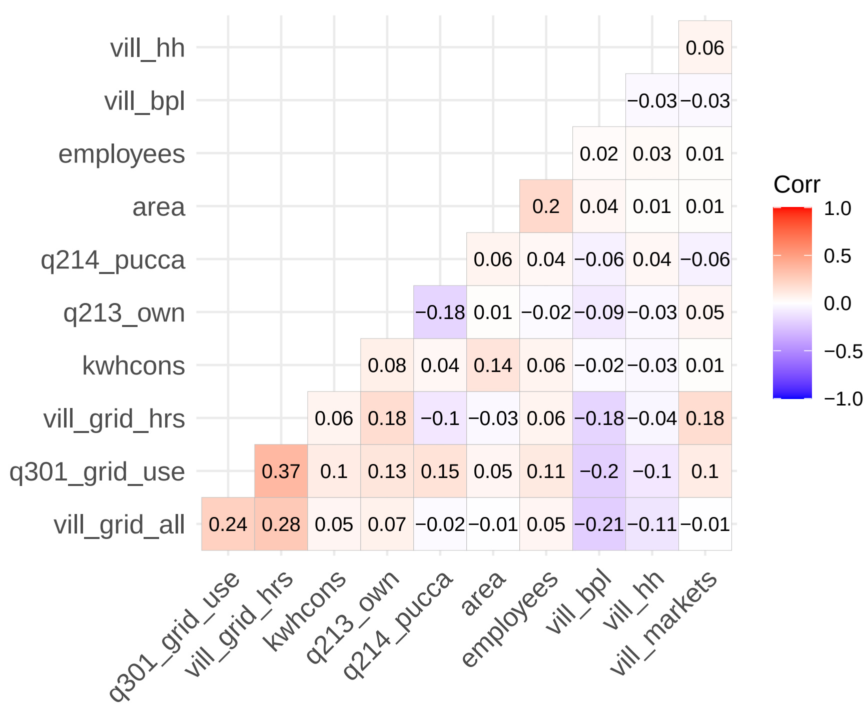

Figure A.2: Chapter 3: REDI dataset (N = 2,004) - Pooled correlation plot.

Table A.1: Chapter 3: Supplementary results, ACCESS grid-connected panel subset (N = 10,556), comparing conditional mean electricity supply hours relative to households that always had access to the energy service.

Dependent Variable:	Daily Supply Hours					
	ICTs	Ent.	Fans	Fridge	Therm.	Mech.
Model:	(1)	(2)	(3)	(4)	(5)	(6)
Variables						
GroupGainedAccess	-0.020	-0.075***	-0.048**	-0.085***	-0.032	-0.027
	(0.022)	(0.018)	(0.019)	(0.032)	(0.031)	(0.037)
GroupLostAccess	-0.037	-0.080***	-0.121***	-0.066*	-0.0010	-0.003
	(0.028)	(0.021)	(0.030)	(0.034)	(0.029)	(0.041)
GroupNeverAccess	-0.022	-0.113***	-0.090***	-0.137***	-0.097***	-0.087**
	(0.042)	(0.019)	(0.032)	(0.029)	(0.028)	(0.034)
Household Size	-0.017**	-0.019**	-0.018**	-0.017**	-0.018**	-0.017**
	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)
Monthly Exp.	0.027***	0.024***	0.025***	0.023***	0.023***	0.024***
	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)
10th Grade +	0.039**	0.029*	0.035**	0.034**	0.032**	0.036**
	(0.016)	(0.015)	(0.015)	(0.015)	(0.015)	(0.015)
Pucca House	0.007	-0.005	0.0001	-0.002	-7.67×10^{-5}	0.003
	(0.016)	(0.016)	(0.016)	(0.017)	(0.016)	(0.016)
BPL/AAY	-0.042**	-0.034**	-0.037**	-0.038**	-0.036**	-0.038**
	(0.016)	(0.016)	(0.016)	(0.016)	(0.016)	(0.016)
SC/ST	-0.044**	-0.039**	-0.038**	-0.041**	-0.037**	-0.041**
	(0.018)	(0.018)	(0.018)	(0.018)	(0.019)	(0.019)
Fixed-effects						
Year (2)	Yes	Yes	Yes	Yes	Yes	Yes
Village (670)	Yes	Yes	Yes	Yes	Yes	Yes
Fit statistics						
Observations	10,519	10,519	10,519	10,519	10,519	10,519
R^2	0.59584	0.59719	0.59654	0.59653	0.59678	0.59631
Within R^2	0.00536	0.00868	0.00709	0.00707	0.00768	0.00652

Clustered (Village) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

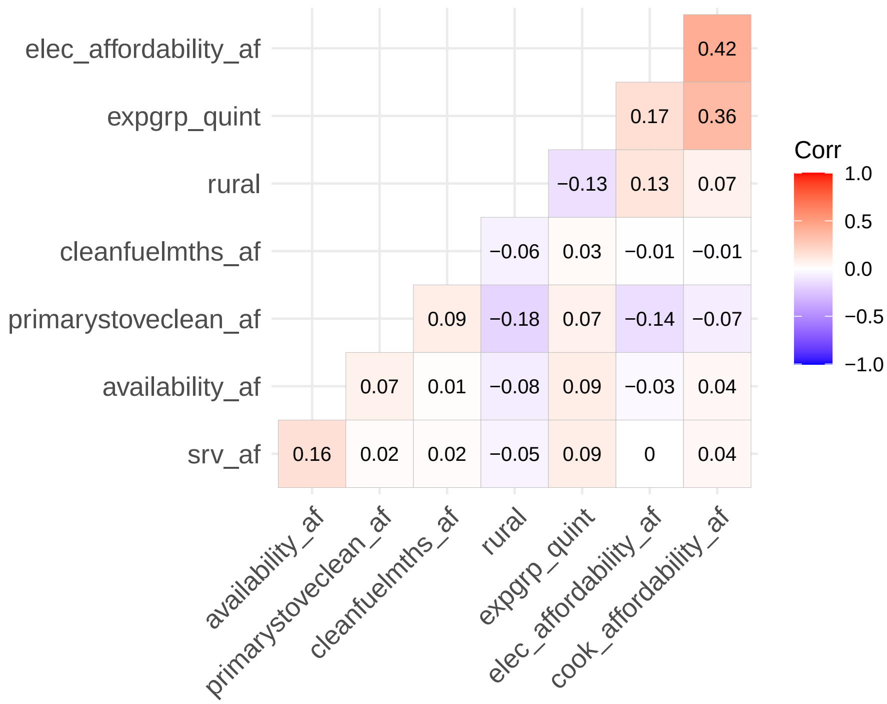

Figure A.3: Chapter 4: MTF dataset (N = 37,111) - Pooled correlation plot.

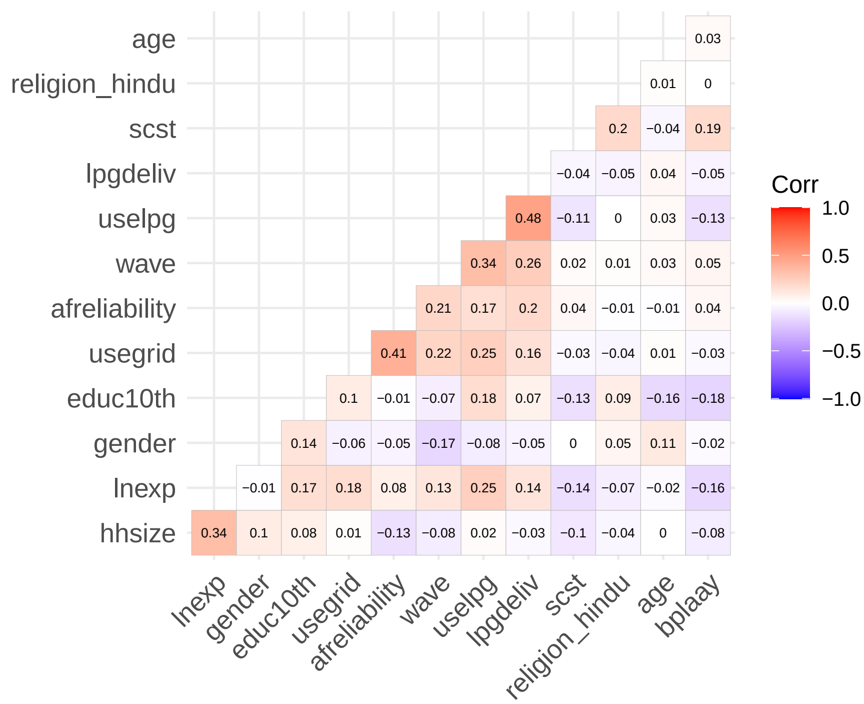

Figure A.4: Chapter 4: ACCESS dataset (N = 17,634) - Pooled correlation plot.

Appendix B

Paper 1

Paper 1 is titled *"A critical review of modern approaches for multidimensional energy poverty measurement"*, (Pelz, Pachauri, & Groh, 2018).

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The latest version of this paper can be found here: `https://doi.org/10.1002/wene.304`

How to cite this paper:
Pelz, S., Pachauri, S., & Groh, S. (2018). A critical review of modern approaches for multidimensional energy poverty measurement. Wiley Interdisciplinary Reviews: Energy and Environment, e304. `doi:10.1002/wene.304`

Appendix C

Paper 2

Paper 2 is titled *"Measuring and explaining household access to electrical energy services: Evidence from rural northern India"*, (Pelz & Urpelainen, 2020).

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This paper uses the ACCESS dataset, which was produced by the Council for Energy, Environment and Water, the National University of Singapore and the Initiative for Sustainable Energy Policy at Johns Hopkins University. ACCESS is a representative panel survey dataset of households in rural areas of the six states with the highest electricity access deficit in India. The surveys were conducted in two waves, in 2014–15 (N = 8563 in 714 villages) and 2018 (N = 9072 in 756 villages). Further detail of the sampling strategy, data collection approach and limitations can be found here: https://doi.org/10.7910/DVN/AHFINM.

The latest version of this paper can be found here: https://doi.org/10.1016/j.enpol.2020.111782. An open-access version of the paper published by SSRN can be found here: https://ssrn.com/abstract=3660805. A replication archive is available here: https://doi.org/10.7910/DVN/JXPOYF.

How to cite this paper:
Pelz, S., & Urpelainen, J. (2020). Measuring and explaining household access to electrical energy services: Evidence from rural northern India. Energy Policy, 145, 111782. doi:10.1016/j.enpol.2020.111782

Appendix D

Paper 3

Paper 3 is titled *"Electrification and productive use among micro- and small-enterprises in rural North India"*, (Pelz, Aklin, & Urpelainen, 2021).

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This paper uses the REDI dataset, which was produced by Smart Power India (an initative of the Rockefeller foundation) and the Initiative for Sustainable Energy Policy at Johns Hopkins University. REDI is a cross-sectional survey dataset of 2,004 small- and micro enterprises from similar rural villages in Bihar, Uttar Pradesh, Rajasthan and Odisha. Further detail of the sampling strategy, data collection approach and limitations can be found here: `https://doi.org/10.7910/DVN/1ZNLUY`.

The latest version of this paper can be found here: `https://doi.org/10.1016/j.enpol.2021.112401`. A replication archive is available here: `https://doi.org/10.7910/DVN/YAGQ6P`.

How to cite this paper:
Pelz, S., Aklin, M., & Urpelainen, J. (2020). Electrification and productive use among micro- and small-enterprises in rural North India. Energy Policy, 156, 112401. `doi:10.1016/j.enpol.2021.112401`

Appendix E

Paper 4

Paper 4 is titled *"Disaggregated household energy supply measurement to support equitable municipal energy planning in rural Nepal"*, (Pelz, 2020).

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This paper uses a primary household survey dataset from rural Nepal. This was funded by the GIZ Nepal RERA program. RERA is a German-Nepali technical cooperation programme to improve the access of rural households to renewable energy in the country. The German contribution to RERA is provided by the Federal Ministry for Economic Cooperation and Development (BMZ). RERA is jointly implemented by the Alternative Energy Promotion Center (AEPC), Government of Nepal, and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. Further information on the RERA program can be found here: `https://www.giz.de/en/worldwide/73840.html`.

The latest version of this paper can be found here: `https://doi.org/10.1016/j.esd.2020.08.010`. A replication archive can be provided upon request and following consent provided by GIZ Nepal.

How to cite this paper:

Pelz, S. (2020). Disaggregated household energy supply measurement to support equitable municipal energy planning in rural Nepal. Energy for Sustainable Development, 59, 8–21. `doi:10.1016/j.esd.2020.08.010`

Appendix F

Paper 5

Paper 5 is titled *"Application of an alternative framework for measuring progress towards SDG 7.1"*, (Pelz, Pachauri, & Rao, 2021).

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This paper uses nationally representative survey data from 10 countries countries gathered under the World Bank's Energy Sector Management Assistance Program (ESMAP) Multi-tier Framework for Measuring Energy Access (MTF) surveys. As of writing, nationally representative survey data is available for Rwanda, Ethiopia, Cambodia, Myanmar, Honduras, Nepal, Kenya, Niger, Sao Tome and Principe and Zambia. Further detail of the sampling strategy, data collection approach and limitations can be found at `https://energydata.info`.

The latest version of this paper can be found here: `https://doi.org/10.1088/1748-9326/ac16a1`. A replication archive is available here: `https://doi.org/10.7910/DVN/DP2V5I`.

How to cite this paper:
Pelz, S., Pachauri, S., & Rao, N. (2021). Application of an alternative framework for measuring progress towards SDG 7.1. Environ. Res. Lett. 16 084048. `doi:10.1088/1748-9326/ac16a1`

Appendix G

Paper 6

Paper 6 is titled *"Energy access for marginalized communities: Evidence from rural North India, 2015–2018"*, (Pelz, Chindarkar, & Urpelainen, 2021).

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This paper uses the ACCESS dataset, which was produced by the Council for Energy, Environment and Water, the National University of Singapore and the Initiative for Sustainable Energy Policy at Johns Hopkins University. ACCESS is a representative panel survey dataset of households in rural areas of the six states with the highest electricity access deficit in India. The surveys were conducted in two waves, in 2014–15 (N = 8563 in 714 villages) and 2018 (N = 9072 in 756 villages). Further detail of the sampling strategy, data collection approach and limitations can be found here: `https://doi.org/10.7910/DVN/AHFINM`.

The latest version of this paper can be found here: `https://doi.org/10.1016/j.worlddev.2020.105204`. A replication archive is available here: `https://doi.org/10.7910/DVN/YNDP93`.

How to cite this paper:
Pelz, S., Chindarkar, N., & Urpelainen, J. (2021). Energy access for marginalized communities: Evidence from rural North India, 2015–2018. World Development, 137, 105204. `doi:10.1016/j.worlddev.2020.10504`

Appendix H

Formal statements

Eidesstattliche Versicherung

Ich erkläre hiermit an Eides Statt, dass ich die vorliegende Arbeit selbstständig verfasst und andere als in der Dissertation angegebene Hilfsmittel nicht benutzt habe; die aus fremden Quellen (einschließlich elektronischer Quellen, dem Internet und mündlicher Kommunikation) direkt oder indirekt übernommenen Gedanken sind ausnahmslos unter genauer Quellenangabe als solche kenntlich gemacht. Zentrale Inhalte der Dissertation sind nicht schon zuvor für eine andere Qualifikationsarbeit verwendet worden. Insbesondere habe ich nicht die Hilfe sogenannter Promotionsberaterinnen bzw. Promotionsberater in Anspruch genommen. Dritte haben von mir weder unmittelbar noch mittelbar Geld oder geldwerte Leistungen für Arbeiten erhalten, die im Zusammenhang mit dem Inhalt der vorgelegten Dissertation stehen. Die Arbeit wurde bisher weder im Inland noch im Ausland in gleicher oder ähnlicher Form einer anderen Prüfungsbehörde vorgelegt.

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Ich erkläre ausdrücklich, dass keine früheren Promotionsversuche der Bewerberin bzw. des Bewerbers stattgefunden haben.

Setu Pelz, Melbourne, 01.09.2021

Ich erkläre ausdrücklich, dass keiner der eingereichten Beiträge aus einer früheren Qualifikationsarbeit stammt.

Setu Pelz, Melbourne, 01.09.2021