Energy Systems Carbon Dependence: A Systematic Review of the Literature and Measurement Framework for Remote Northern Communities

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Abbreviations

CASES	Community Appropriate Sustainable Energy Security
CO_2	Carbon dioxide
DFID	The Department for International Development
GDP	Gross Domestic Product
HWWD	Household Well-being sensitivity to changes in Well-being Drivers
IAEA	International Atomic Energy Agency
ICE	Indigenous Clean Energy
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISCF	Infrastructure Sensitivity to Changes in Fuel quantity
NRCan	Natural Resources Canada
QCA	Qualitative Comparative Analysis
SDG	Sustainable Development Goals
SCC	Social Cost of Carbon
UNEP	United Nations Environment Programme
WDFC	Well-being Driver sensitivity to Fuel Change

Abstract

Carbon dependence is a recurrent concept in the energy systems sustainability literature, particularly in discussions of energy transitions and their socio-economic and environmental implications. However, a standardized definition and a community-appropriate measurement framework still need to be developed. As the ambition to reduce carbon dependence across remote northern communities intensifies, the lack of a standardized understanding of the concept could result in inconsistent measurements of carbon dependency levels across communities. Consequently, this could limit the ability to deliver evidence-based resource allocation and identify communities with urgent development priorities when delivering energy transition interventions. This study improves understanding of carbon dependence and dependency in two ways: (i) presents a systematic review of the literature, analyzing how existing studies conceptualize and measure this concept within energy-economic systems, and assessing the suitability of existing measurement frameworks for remote northern communities; (ii) propose a community-appropriate measurement framework for understanding the magnitude of carbon dependence within remote northern communities using a well-being-based approach. The findings from an in-depth analysis of 43 studies reveal a spectrum of implicit conceptualizations across multiple scales of measurement and analysis, with concordant variability in results and interpretations. While the reviewed studies have presented measures for their intended use, the absence of a context-specific measurement of carbon dependency at the community level highlights the need to standardize an appropriate scale-independent definition. The measurement framework proposed in this thesis builds on established principles in multivariate calculus and economics for building carbon dependence indices by fuel types. We hope the priority for future studies will be to apply the proposed framework using real community-level data.

Chapter 1: Introduction

1.1 Background

Globally, reducing dependence on CO_2-emitting energy sources is a popular feature of climate change mitigation policies (IEA, 2021; IPCC, 2023). However, despite decades of academic and policy interest in the global dynamics of carbon consumption and production (Wang & Su, 2019), the conceptual understanding of carbon dependence remains limited. Little effort has been made within the literature to empirically analyze the measurement dimensions and indicators of carbon dependence (Knight, 2019). A structured and comprehensive understanding of the existing conceptualization of carbon dependence could support the development of a measurement system for assessing its magnitude in remote communities.

Many remote northern communities face unique energy challenges, primarily due to their high dependence on imported fossil fuels (Natural Resources Canada (NRCan), 2011; Mercer et al., 2020). Although reducing this dependence has been identified as a key to unlock opportunities for improved energy security across these communities (IEA, 2022; Pembina Institute, 2021b), a data-driven understanding of the extent of dependence is essential for supporting effective policy and planning.

The debatable nature of dependence-based concepts (Fine & Glendinning, 2005) requires the application of a rigorous and systematic approach to develop a measurement system to evaluate the magnitude of carbon dependence within this context. Developing a measurement system should involve selecting contextually relevant indicators, determining the methods for measuring these indicators, and choosing an appropriate methodology for aggregating values. A systematic review of existing literature supports the understanding of standardized variables for carbon dependency that could be integrated into a measurement system tailored to remote communities.

For the purpose of this study, 'remote northern communities' refers to physical spaces with permanent human settlements that are removed from population and commercial centers. These mostly rural communities often have limited access to the full range of services typical in urban areas, including non-connectivity to regional energy networks, and are often accessible only under specific seasonal or weather conditions (Schmidt, 2008; NRCan, 2011). Examples include indigenous communities such as Attawapiskat in Ontario and Old Crow in Yukon.

This thesis provides a detailed analysis of existing conceptualizations of energy-related carbon dependence and a measurement framework for community-level assessment. Chapter 2 presents a systematic review of the extant literature on the concept and identifies gaps in existing research. Chapter 3 presents a framework to assess the magnitude of carbon dependence using established methods from multivariate calculus and economics.

The measurement framework is also applied to a simple hypothetical scenario to demonstrate its practical application. Finally, Chapter 4 concludes with key insights from the analysis and outlines priorities for future research.

1.2 Reflexivity statement

It is important to highlight some information about my experiences and the research platform that has influenced the direction of this thesis. I hold a bachelor’s degree in physics and post-graduate training in economic development and impact evaluation. My professional experience includes managing power system development projects and leading economic development evaluation projects in Africa. The unique blend of experience and training as a physical scientist has shaped my interest in measurement-related questions.

Over the years, I have been actively involved in evaluation projects designed to answer local economic and energy policy questions across themes such as energy transition and urban resilience while working for the British Government Department for International Development in Africa. My interest in dependence studies started from a personal reflection on my experiences as a teenager living in Africa, where daily and sometimes weeklong power outages hindered access to critical services necessary for my overall functioning. These power cuts were mainly due to insufficient natural gas and diesel supply needed to support the power grid that supports the community.

Reading debates within the literature on dependence-based concepts further piqued my interest in understanding energy-related carbon dependence. I internally questioned the multidimensionality of carbon dependence within energy systems by asking: What dimensions should be measured to truly understand its magnitude? Is measuring carbon dependence solely about quantifying carbon emissions?

Participating in the Community Appropriate Sustainable Energy Security (CASES) project influenced the interest in remote northern communities. One of the objectives of CASES is to train early-stage researchers to transform energy systems and promote sustainable energy patterns in northern and indigenous communities. I believe that this thesis supports the objectives of CASES by providing a tool (the measurement framework) to inform decisions to advance sustainable energy solutions and the energy security of these communities.

1.3 Study purpose and research questions

This thesis aims to enhance understanding of carbon dependence in energy systems by presenting a structured analysis of the state of knowledge production on the concept and a measurement system to assess its magnitude in remote northern communities. The two main questions that have guided this thesis are:

1. How has carbon dependence been conceptualized and measured in the energy systems literature?
2. What are the elements of a measurement system designed to quantify the magnitude of energy-related carbon dependence within remote northern communities?

This thesis represents a significant step towards consolidating the fragmented knowledge space on carbon dependence. It provides foundational analysis that could support future work to evaluate the magnitude of dependence on carbon-based energy sources using actual data collated from communities.

1.4 Approach

A mixed-methods approach was adopted to achieve the objective of the study. Chapter 2 is a qualitative systematic review of 43 studies focused on carbon dependence within the energy systems literature. In this review process, I considered a range of definitions, methodology, focus, and scale of analysis. In Chapter 3, I proposed a framework to measure carbon dependence using principles based on established implicit notions of dependence in mathematics and elasticity estimates for understanding the magnitude of dependence across remote communities.

The carbon dependence indices incorporate the evaluation of total emissions estimates from local fuel consumption as an independent variable and community well-being as a dependent variable. This chapter includes a hypothetical scenario to show the practical steps required to employ the measurement system using mock survey data. Chapter 4 concludes the thesis with a brief discussion on the significance of this study to the field and future work to expand the scope of the analysis.

Chapter 2: A systematic review of the literature on energy systems carbon dependency

2.1 Introduction

Decarbonizing energy systems alongside the pursuit of distributed, renewable energy is critical for enhancing energy security across remote northern communities (IEA, 2022). The continued reliance on diesel and other carbon-based, non-renewable energy sources has economic and well-being impact on these communities (Lovekin & Heerema, 2019; IEA, 2022; Touchette et al., 2017). In response, policies and projects have been developed to increase clean energy production and address the unique challenges of reducing carbon dependency in these areas (Pembina, 2021b). These local decarbonization efforts also contribute to the achievement of global development goals aimed at reducing carbon dependency and achieving emission reduction targets (UNEP, 2009).

Despite global acknowledgment of the importance of reducing carbon dependence at various levels (national, regional, and community), existing analysis on the concept seem to focus predominantly on urban and macro-level context (Phillips & Dickie, 2015). Assessing the nature and extent of carbon dependence of communities is essential to guide evidence-based resource allocation in energy development and policy formulation scenarios (Zhang & Zhou, 2018; Raimi, 2021).Thus, it is important to employ context-appropriate measurement frameworks that acknowledge and account for the uniqueness of each community.

The terms carbon dependence and carbon dependency broadly refer to the social, spatial, and economic reliance of a particular region on non-renewable carbon-based fuels (Hao et al., (2020). As an illustration, we could consider a region generating a composite good through some input and output channels. In discussing carbon dependence, we are interested in describing the existence of a reliance on carbon within the input or output channel of a region. For example, a region whose economic viability is based on coal mining (output-focused) and another region that relies on importing diesel fuel to run generators (input-focused) would both be viewed as carbon-dependent. At a deeper level, one can ask more detailed questions about carbon dependency, which is the degree to which this reliance mechanism constrains development possibilities. An input-focused understanding of carbon dependency is relevant for evidence-based policy, program development, and investment in energy transitions for remote communities.

Generally, there is no unified notion of dependency; historical shifts and variations in meaning have occurred within economic, social, and political discourse (Fraser & Gordon, 1994). In the classification of dependency presented by Fraser & Gordon within three major fields, the economic interpretation is based on the reliance of one entity on another for subsistence. The economic notion of dependency is further categorized by Huang & Słomczyński (2003) into three dimensions: international trade, external debt, and foreign investment. From a political perspective, dependency is characterized by subjugation to an external ruling authority. Meanwhile, within a psychological context, it is described by traits related to emotional neediness. Despite the common usage of carbon dependency within energy studies, a comprehensive analysis considering its dimensions is scant (Knight, 2019). In remote northern communities with a unique blend of geographical, economic, and sociocultural factors, each influencing carbon dependence patterns in distinct ways (Vodden et al., 2021), efforts to reduce carbon dependency could be limited without a clear definition within the literature and a context-specific measurement framework appropriate at the community level. Without such a framework, it becomes difficult to objectively identify communities most in need of energy development interventions to break their cycle of carbon dependence.

The primary objective of this chapter is to explore how carbon dependence and dependency are conceptualized in the literature. We analyzed studies that, at least implicitly, examine the concepts within energy and economic systems. This review aims to serve as a foundational assessment, informing the next chapter dedicated to developing a measurement framework for remote northern communities.

2.2 Methodology

A systematic literature review was adopted, following the guidelines described in the Preferred Reporting Items for Systematic Reviews and Meta-analyses statement (Moher et al., 2009). This approach enabled the identification of relevant studies connected to the review questions while mitigating the potential for bias in the literature search and assessment process. The review was structured based on three main search queries, as shown in Figure 1.

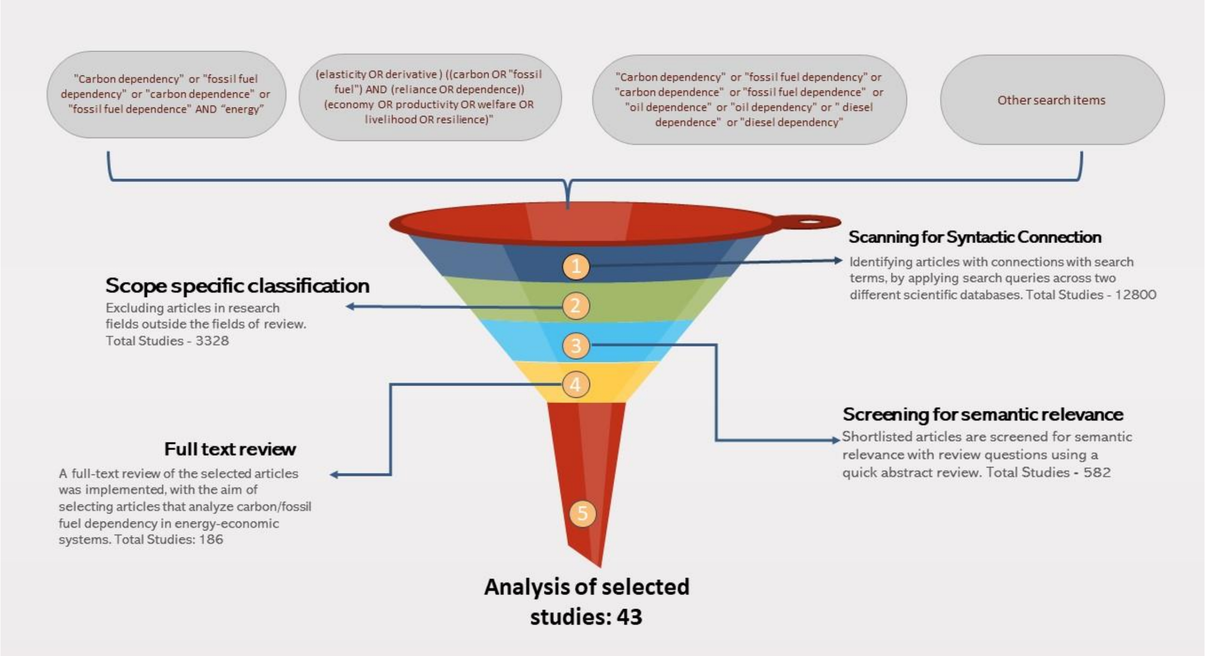

Figure 1.1: Literature search and review process. This illustrates the approach adopted for filtering and selecting relevant studies for the literature review process. The process starts with applying broad search terms across two scientific databases, which yielded a large number of studies syntactically connected to the search terms. A scope-specific classification was done to remove those studies outside the relevant research fields. These shortlisted articles are then screened for semantic relevance through a quick abstract review, resulting in 186 studies. Finally, a detailed full-text review of these articles was conducted, leading to the final selection of 43 studies that are most relevant to the review objectives.

The first query captured a basic combination of terms, namely combining carbon dependency or fossil fuel dependency with energy: "carbon dependency" OR "fossil fuel dependency" OR "carbon dependence" OR "fossil fuel dependence" AND “energy”. This was followed by a second search query that examined articles that employed economic concepts and numeric approaches to assess dependency and its influence on various socio-economic outcomes: "(elasticity OR derivative) ((carbon OR "fossil fuel") AND (reliance OR dependence)) (economy OR productivity OR welfare OR livelihood OR resilience)". The third search query captured articles that may employ the concept(s) of dependency in different forms: “carbon dependency” OR "fossil fuel dependency” OR "carbon dependence" OR "fossil fuel dependence" OR "oil dependence" OR "oil dependency" OR " diesel dependence" OR "diesel dependency".

Additionally, we conducted a parallel search for several “other” terms to identify articles that might examine implicit notions of carbon dependency in different contexts without explicitly referring to the terms identified in our major search queries. These terms included energy dependence in off-grid communities, carbon reliance or fossil fuel reliance and energy, diesel dependence in remote communities, carbon performance index, carbon intensity measures or fossil fuel measures, energy self-sufficiency in remote communities, and indicator system(s) for measuring energy sustainability. This parallel search served as a reference for the scope of coverage of our major search queries, and we reviewed only the first 60 to 80 results generated by these other terms. The search queries and terms were explored using two search engines, Google Scholar and Web of Science, across all article fields, including the title, abstract, and main content. These two databases were selected for their search capabilities and indexing functions, which enabled the categorization of relevant studies and quality assessment.

The immediate output from the first stage generated thousands of articles, including articles in out-of-scope fields like chemistry, telecommunications, biochemistry, and agriculture. A filter function on the search databases was thus applied to eliminate articles in such fields outside the scope of this study. This process is titled “Scope Specific Classification” in ***Figure 1***. Subsequently, we conducted a first-order semantic analysis of the titles and abstracts of the first shortlist to differentiate between studies that casually mention carbon dependency in the text but without any substantive focus or emphasis and those that specifically focus on analyzing the concept, at least implicitly. For example, while numerous studies include phrases like "reducing carbon dependency" or "reducing dependence on fossil fuels" in their introductory sections, these mentions were often in passing and not central to the primary objective of the studies.

Through the semantic analysis, we generated a curated list of articles relevant to our review objective. At the final stage, we did a content review of the final shortlist of articles to understand the degree of connectedness to our research objectives, taking a more in-depth review of the conceptual ideas proposed in the studies and the methodology employed. As shown in ***Figure 1,*** this full-text review process was only done for about 180 articles.

No restrictions were applied to the publication years during the search and review process, allowing for the examination of studies from various periods. This approach provided a comprehensive perspective on the literature within academic and non-academic discourse.

The final list of 43 selected studies was examined across four domains:

1. **Definition:** Whether and how the articles defined or described carbon dependency, considering explicit definitions, theoretical foundations and the operational characteristics employed by the studies.
2. **Methodology implemented:** The types and diversity of methodologies employed, including the dimensions of analysis (e.g., economic, ecological, political) and the specific measurement indicators used.
3. **Scale of analysis:** The geographical scope of research, categorizing studies as either national/multinational or regional/community-scale analyses.
4. **Focus:** Whether the research concentrated on production-based dynamics, such as export or extraction of carbon-based energy sources, or consumption-level factors, such as patterns of household-based utilization, electricity generation, transportation, and general regional delivery of energy services.

2.3 Results

Approximately 60% of the studies from the sample focused on evaluating the extent of dependency and subsequent implications for the studied region. For example, Acevedo & Lorca-Susino (2021), Evans (2008), Fang (2011), Gupta et al. (2021), Halser & Paraschiv (2022), Jacal et al. (2022) and Thombs (2022) focused on assessing trends in carbon dependency and associated impacts across a range of areas, including state-level housing returns (returns on housing investments within a specific state), implications for well-being, and regional economic costs. Hou et al. (2021) examine the effects of carbon dependency on public response to climate change, revealing that greater national dependency hinders effective public action. This is similar to the analysis by Knight (2019) on the influence of carbon dependency on public perceptions of climate-related risks. Busch et al. (2011) and Hoffmann and Busch (2008) presented time-sensitive approaches for dependency assessment within a carbon performance framework. Both studies evaluated carbon intensity changes over time as a benchmark for corporate carbon performance. Mertins-Kirkwood (2018) investigated dependency in the context of labour force impacts and the economic contribution of carbon-based industry. Various other authors (e.g., Chen et al., 2020; Hou et al., 2021; Jain, 2019; Ligus & Peternek, 2021) explored different direct and indirect measurement dimensions of carbon dependency.

Approximately 25% of the reviewed studies focused on the factors influencing the ability of a region to reduce its dependence on fossil fuels and implement low-carbon solutions. For example, Henderson & Sommer (2022) and Xue et al. (2021) provided an unconventional lens in the analysis of dependency by examining the role of foreign development aid. Their work introduces a geopolitical layer to dependency discussions, revealing how international aid and fossil fuel-based sector investments may influence national-scale carbon dependency. Studies by Evans & Phelan (2016); Hao et al. (2020); Phillips & Dickie (2015) explored socio-political factors, including how civil society campaigns against regional fossil fuel-based development and public perception of climate change may influence carbon dependency trajectories. Other scholars (including Acevedo & Lorca-Susino, 2021; Evans, 2008; Ide, 2020; Riedel, 2021; Vergara, 2018) introduce the influence of national energy-based climate policy in shaping carbon dependency patterns and highlight regional-level adaptive strategies adopted to reduce dependency. Beyond state policy, Vieira et al. (2022) demonstrate how international oil companies are also contributing to carbon dependence reduction. Specifically, the author uncovered strategies adopted to facilitate energy transition among major European oil companies—in the form of emission trading systems, emissions mitigation through operational improvements, and an overall corporate strategic transition into non-carbon sectors.

Finally, five studies specifically examined the distribution of benefits in reducing carbon dependency. These studies explored benefits not only from environmental dimensions but also from economic and social dimensions. For instance, Kuik (2003) considers the trade-offs and benefits of reducing carbon dependency within the European Union (EU). The study by Kuik developed climate policy scenarios for evaluating carbon reduction implications for economic efficiency and energy security. Similarly, Xue et al. (2021) consider the ecological benefits of constraining foreign direct investment in fossil fuel industries, particularly in South Asia, adding a critical environmental lens to the discussion on benefits, revealing how reduced carbon consumption can yield direct, measurable ecological gain. Portugal-Pereira & Esteban (2014) showed how reduced dependence on fossil fuels and increasing grid-connected renewable energy enhance energy security and reduce import dependency.

Sections 2.3.1 to 2.3.4 present the detailed results of the analysis of sample studies across four domains: definition, methodology, scale, and focus. See ***Appendix A*** for the list of reviewed studies categorized across the domains of analysis.

2.3.1 Definition

Analysis of the reviewed studies revealed considerable inconsistency in the definition of carbon dependency. About 60% of the studies reviewed did not offer any operational or conceptual definition, leaving gaps in understanding of how the concept was framed within the studies. Among the studies that did provide a form of definition, 76% were operational, i.e., the definitions were not explicitly stated but could be implicitly derived from the indicators and metrics used in the study. For example, in Acevedo & Lorca-Susino (2021), carbon dependency was operationalized based on the impact of changes in carbon prices on economic growth. In Phillips & Dickie (2015), carbon dependency was considered in the form of carbon emissions by sector contributions; focusing on household domestic usage, transportation, industry and commerce, land use and forestry. Thombs (2022) defined the concept as the over-specialization in fossil fuel extraction. For Mertins-Kirkwood (2018), carbon dependency is viewed as the contribution of the fossil fuel industry to the overall economy. In Raimi (2021), fossil fuel dependency was evaluated as a measure of the vulnerability of regions in energy transition scenarios.

A range of definitions were identified among the studies that provided a specific conceptual definition of carbon dependency. For example, Hao et al. (2020) offered a generic definition, framing carbon dependency as the “degree to which a nation's or region's economy relies on the fossil fuel industry.” Portugal-Pereira & Esteban (2014) conceptualize carbon dependency as the share of imported fossil fuels to total supplied electricity, while in Ren & Dong (2018), carbon dependency is considered a measure of self-sufficiency, i.e., the share of total electricity generated by fossil fuels. Focused specifically on corporate-level analysis, Hoffmann & Busch (2008) introduce a time consideration, conceptualizing carbon dependency as the change in the physical carbon performance of a company within a given period.

When studies do not provide any definition but present only a measurement framework, it is unclear how the authors defined the concept. For example, in Hou et al. (2021), no explicit definition was provided, but carbon dependency is expressed in four dimensions: economic development, energy security, overall living conditions, and environmental conditions. There are only two articles in the sample that present both operational and conceptual definitions: Hao et al. (2020) operationalize carbon dependency as the ratio of the total CO_2 emissions of a region to its Gross Domestic Product (GDP). Similarly, Hoffmann & Busch (2008) provide an operational definition: the percentage change in carbon intensity over time. These diverse interpretations of carbon dependency raise questions about the possibility of a standardized, globally applicable definition that is independent of scale, which is crucial for developing measurement methodologies appropriate to different scales of analysis.

2.3.2 Methodology employed by reviewed studies

A range of methodological frameworks were adopted, using qualitative and quantitative designs, across the reviewed articles. About 35% of the articles employed a qualitative approach to assessing carbon dependency, including Qualitative Comparative Analysis (QCA), discourse analysis, and systematic literature reviews. For example, Ide (2020) deployed QCA to investigate how fossil fuel dependency influences national climate policy development, showing that countries that have historically built economic prosperity on fossil fuel production (e.g., Saudi Arabia) and those dependent on fossil fuel production amid economic difficulty (e.g., Argentina and Ukraine) tend to be less inclined to implement stringent climate policies. Evans (2008) applied discourse analysis in their study of the influence of civil society campaigns against carbon dependence. Other studies that adopted qualitative approaches include the analysis by Riedel (2021) on carbon dependency and Polish government climate-related policy strategies. The study by Riedel reveals that the climate strategies adopted by the ruling political party have been informed by the populist notion of green conservatism and a unique type of environmental nativism, where locals prioritize their right to exploit natural resources over environmental protection, influencing the dynamics of carbon-dependent energy policy and environmental preservation policy. In the study by Vergara (2018), a historical analysis of energy regimes in Mexico from the nineteenth century adopted both primary and secondary data sources to explore the environmental consequences of the shift in fossil fuel dependence and the role of institutional actors in this process. A significant gap in current qualitative research is the lack of investigation into the evolution of the meaning and application of carbon dependence within the literature. Understanding the historical usage of the concept within energy systems studies and policy discussions could contribute to a useful assessment of the shifts in meaning and contemporary notions.

Most of the studies in our sample applied quantitative methods to analyze carbon dependency. Some common techniques include the use of regression models, elasticity estimation techniques, and composite index systems. For example, Xue et al. (2021) use econometric analysis to explore the benefits of reducing fossil fuel dependency among South Asian nations; Chang & Chang Hwang, (2013) provide elasticity estimations of emissions along economic and demographic factors (population, per capita GDP, energy efficiency) across 132 countries. Similarly, Benedictow et al. (2013) evaluated the vulnerability of the Russian economy to changes in oil prices in an analysis to understand the degree of oil dependency, considering effects across macroeconomic indicators (interest rates, labour market dynamics, exchange rates, etc.); while Chen et al. (2016) examined the relationship between economic growth and carbon dependency through panel co-integration and error-correction models. More complex regression modelling was applied by Gupta et al. (2021) where they adopted a vector autoregression model to understand the impact of oil dependency on housing investments returns in the United States. Other works, like those by Halser & Paraschiv (2022) and Henderson & Sommer (2022), also adopted regression models to explore the impact, effects, and drivers of dependency, from the influence of fossil fuel dependence on public opinion regarding climate change to energy sector aid contribution to fossil fuel dependence in recipient countries.

Some studies also employed composite index methodologies. For example, Portugal-Pereira & Esteban (2014) applied a set of indicators to assess fossil fuel dependence and electricity generation security in Japan while Hou et al. (2021) applied the recently developed Grey Relational Analysis (Liu et al., 2022) to construct an energy dependence model across energy sources to showcase the state of carbon dependence in China. One of the studies in the sample, Vieira et al. (2022), considered both qualitative and quantitative approaches. Vieira et al. used document analysis combined with carbon emission data analysis from 10 European international oil companies to identify and analyze the decarbonization strategies adopted by these companies. Considerable variability was observed in the dimensions of interest across the sample of quantitative studies and in the indicators selected for measurement across those dimensions. Some common dimensions include energy security, economic development, environment, and built environment. Some indicators identified across the studies that adopted composite measures are outlined in ***Appendix A (Table A.2).***

The reviewed studies less frequently provide a rationale for the selection of dimensions and indicators. Furthermore, most studies fail to describe how each dimension supports the specific conceptualization of carbon dependency employed. While some studies define each dimension presented, there is often a limited connection to a robust conceptual foundation underlying what is being measured.

This assessment also identified extensive and intensive measures[1] of carbon dependency. Intensive measures are properties that are independent of the size of the system of analysis, while extensive measures depend on the size of the system (Redlich, 1969). This categorization is important in understanding the typology of variables employed across the studies and its influence in comparing regions. All reviewed studies that applied quantitative methodology had some form of intensive measure in their analysis, with some using extensive and intensive variables. For example, Chen et al. (2020) presented a model for measuring fossil fuel dependence involving both extensive (e.g., CO_2 emissions estimates) and intensive (e.g., per capita GDP) measures. Similarly, in Mertins-Kirkwood (2018), some indicators were extensive (e.g., jobs in fossil fuel-based industry), while others were intensive (e.g., the share of fossil

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[1] *This categorization was adopted from the field of thermodynamics. A detailed explanation can be found in* Redlich (1969) *and further explored in Chapter 3*

industry in GDP estimates). Similarly, in their analysis of dependency across 10 European countries, Marques et al. (2018) apply variables such as energy production from natural gas, coal, and oil (extensive) and variables such as the share of hydro and coal in electricity generation (intensive). Applying intensive measures for carbon dependency provides a more logical measurement tool for comparisons across different scales of analysis. This is important when comparing regions where the size of the context of analysis can vastly differ.

Recent scholarship has presented various quantitative approaches for evaluating carbon dependency at the macroscale (national, continental, and regional levels). However, a critical gap remains in the presentation of standardized indicators and a suitable measurement approach in community-scale analysis.

2.3.3 Scale of analysis

The reviewed studies predominantly focus on macro-level analysis. Notably, about 85% of the studies focus on national to multi-country analysis; 35% of the reviewed studies focus on national scale analysis. Only about eight of the 43 articles reviewed focus their analysis at subnational levels (i.e., regional, state, provincial, and community). The geographic spread of research on carbon dependency is also revealing. The United States (Busch et al., 2011; Greene, 2010; Gupta et al., 2021; Raimi, 2021; Thombs, 2022), Europe (Acevedo & Lorca-Susino, 2021; Bhattacharyya, 2009; Chalvatzis & Ioannidis, 2017; Hao et al., 2020; Kuik, 2003; Lane & Vanderschuren, 2009; Ligus & Peternek, 2021; Marques et al., 2018; Vieira et al., 2022), and Asia (most notably China and Japan in: Chen et al., 2020; Fang, 2011; Hou et al., 2021; Jain, 2019; Portugal-Pereira & Esteban, 2014; Wei-Yu & Nian, 2013; Zhang & Zhou, 2018); have been the focal point of scholarship. Some country-level research was also identified; for example, Brazil (Fernandes et al., 2019; Solingen, 1991), Australia (Evans & Phelan, 2016; Evans, 2008), Mexico (Vergara, 2018), Russia (Benedictow et al., 2013), and Canada (Mertins-Kirkwood, 2018), to name a few. Some studies have also considered multiple countries. For example, Knight (2019) employed a cross-national framework across 100 countries to investigate the relationship between carbon dependency and public opinion on climate change. The authors demonstrated that countries with higher carbon emissions per capita have a lower perception of climate change threats and a lower perception of human influence on climate change. The only study in our sample that examined community-level carbon dependency is Phillips & Dickie (2015). Phillips & Dickie assessed awareness of carbon dependency and its influence on climate change perception and mitigation actions but did not provide a measurement framework for in this context. This finding reinforces our initial submission on the need for a comprehensive framework for measurement at the community level.

Finally, among the seven articles that focused on regional scale analysis, only Raimi (2021) and Wei-Yu & Nian (2013) present some form of comprehensive (at least relatively) measurement framework for carbon dependency. Although the measurement system provided by Wei-Yu & Naian focused on “low carbon economy”, the research implicitly describes carbon dependence using four main indicators (with 20 sub-indicators): energy consumption efficiency, low carbon economy, low carbon environment, and living conditions (indicators connected to residential energy consumption). The rationale for selecting indicators in Wei-Yu & Naian study is also unclear. It is unclear how these indicators provides the magnitude of carbon dependence, mainly because of the limited basis of definition. Although the analysis presented by Raimi is focused on estimating fossil fuel dependence, the indicators presented are linked to estimating energy transition vulnerability at the regional level.

2.3.4 Focus

Most of the reviewed studies focused primarily on consumption-related dimensions. Nine studies considered both production and consumption in their analysis, while two focused solely on production-based analysis. The studies that concentrated on consumption based their analysis on household and corporate-level energy systems, urban mobility energy consumption, and other demand-side analyses. They also considered the impacts of carbon consumption across macroeconomic indicators. For example, Chen et al. (2016), Gupta et al. (2021), and Halser & Paraschiv (2022) investigated the macroeconomic impact and trends in consumption using GDP indicators and composite measures comprised of consumption-based indicators. These studies reveal important insights on the differential effects of carbon dependence on economies at varying stages of development, including the positive relationship between carbon price-related demand shocks on housing returns and dependence effects on energy supply security. In Hou et al. (2021), composite index methodology was applied to assess consumption-related carbon dependency, revealing a declining trend in the energy dependence of China on fossil fuels, based on consumption indicators across economic development dimensions. At a more localized level, Phillips & Dickie (2015) used carbon consumption (emissions) estimates to evaluate dependency in an analysis of awareness and transition narratives across four villages in England. The authors reveal that while there was a high degree of awareness of carbon dependency regarding consumption, this awareness did not translate into substantial mitigation or adaptation actions. Fernandes et al. (2019) and Lane & Vanderschuren (2009) explore levels of resilience and measures to reduce vulnerability induced by consumption-based dependence. The analysis by Fernandes et al. revealed a positive correlation between low-income districts and urban mobility resilience when faced with threats due to fossil fuel dependency. Lane and Vanderschuren suggest that implementing transition measures in isolation for transportation systems is insufficient to bridge the gap between energy demand and supply.

The studies that considered carbon dependency from both consumption and production perspectives were primarily interested in understanding local energy consumption and export-based analysis (i.e., input- and output-based notions of dependence). For example, in Evans & Phelan (2016), the impact of civil society campaigns on reducing carbon consumption and production hegemony in the Hunter Valley, Australia, was explored, illustrating how social movements could be used to raise awareness of the environmental and social costs of carbon dependence and advocate for the transition to a post-carbon society. Production and consumption-induced vulnerability are further explored in Bhattacharyya (2009), and Weisser (2004) where they consider dependence on electricity generation sectors in Europe and small island states. These studies examined economic drivers, particularly carbon price fluctuations and existing carbon import dependency levels, as factors contributing to vulnerability in electricity production.

From a production-only perspective, the reviewed studies tend to focus on carbon exports and other supply market-based perspectives. For example, Greene (2010) considered the cost of oil dependence by analyzing the US oil production market and market monopoly in examining energy security, revealing the economic threat due to oil dependence. The study also reveals that the realistic pathway to oil independence is prioritizing energy security strategies and reducing vulnerability to energy supply disruptions. Benedictow et al. (2013) explore the volatility of the Russian economy by examining its carbon export dependency in scenarios of oil price fluctuations, considering different oil price scenarios and effects on export revenue. This study by Benedictow et al. reveals the effects of higher oil prices in the form of economic growth and increased public and household spending, among other macroeconomic effects.

Overall, results show varied approaches to understanding carbon dependency but with most focus on consumption. However, given the regional to national scales of consumption analyses, there is only limited transferable research to understand suitable indicator(s) to measure consumption-based dependency at the community scale.

2.4 Discussion

The results of this review demonstrate considerable variability in the definition and conceptualization of carbon dependency. The absence of scholarship focused on advancing a standardized definition and measurement indicators influences this ambiguity in the literature, whereby research is mainly grounded in context-specific analysis at different scales but with limited exploration of the broader, transferable lessons and approaches from one context and scale to the next. Without a consensus on meaning and a conceptual framework for assessment, efforts to reduce carbon dependence across different levels may lack a consistent basis for resource allocation, impacting the nature and alignment of policies and projects designed to reduce carbon dependence.

In the context of using evidence to support energy development processes, what is measured influences policies developed (Stiglitz et al., 2009). Policymakers seeking to use an understanding of the magnitude of carbon dependence in various communities to prioritize policy actions may be hindered by the absence of a unified metric for analysis. For instance, in the context of monitoring and assessing the Sustainable Development Goals (SDG), it has been observed that inconsistent definitions of indicators and diverse measurement methodologies have complicated the assessment and monitoring of SDG performance by the EU (Lafortune et al. 2020). This inconsistency has posed challenges in identifying policy priorities and actualizing the SDGs within the EU.

The intergovernmental organizations that typically present global shared frameworks for energy systems assessment (for example, the International Energy Agency (IEA) and the International

Atomic Energy Agency (IAEA)) do not have an explicit and comprehensive set of measurement standards specifically for carbon dependency. The definitions presented in IAEA (2005) Energy Indicators for Sustainable Development and corresponding methodologies presented an "energy import dependency" by fuel type, measured as the ratio of net import to total primary energy supply in a given year. However, this metric primarily addresses import reliance rather than providing a direct measurement of carbon dependency.

When dependency is measured in physical science, it is typically about evaluating how one dependent quantity is affected by the changes in the magnitude of an independent quantity (Redish, 2021). This sensitivity-based approach is applied in Benedictow et al. (2013) assessment of oil dependency in the Russian economy, considering the economic effects of changes in oil prices and alternative fiscal policies. However, the indicators measured in the analysis by Benedictow are only relevant in macroscale analysis and may not be helpful in understanding the magnitude of dependence at the community level. This sensitivity approach is similarly applied in Thombs (2022) evaluation of the effect of fossil fuel production and consumption changes on well-being measures. However, the indicators employed are unique based on macroeconomic state-level and mining sector-specific indicators.

Scholars have been so inured to using carbon dependency that the depiction in existing scholarship has been marked with casual interpretations. Instances of this can be found in studies with stated intentions to analyze carbon dependency but only consider simple unidimensional evaluation of carbon emission, consumption, or production measures (e.g., Jain, 2019; Knight, 2019; Mertins-Kirkwood, 2018; Phillips & Dickie, 2015). When used in any measurement context, dependency-based concept should be treated with an understanding of its multidimensionality(Huang & Słomczyński, 2003). Suppose we try to adapt the notion of dependency, as established in mathematics and physical sciences, into a framework for quantifying carbon dependency in a specific context. It is essential to identify the dependent and independent quantities and model their relationship. Such a framework forms a basis for measuring the association between the independent and dependent variables. The choice of dependent variables would logically be relevant to the context of the analysis and the specific research goals. For instance, in the analysis by Thombs (2022) on fossil fuel dependency, well-being was used as the dependent variable, quantified as health-adjusted life expectancy. In the analysis by Benedictow et al. (2013) on oil dependency in Russia, the dependent variable is a multidimensional economic performance indicator that includes government expenditure, inflation, exports, and other macroeconomic factors. In the context of remote communities, it is important to select indicators that are relevant to community assessments. For example, multidimensional indicators like well-being and livelihood are relevant within community-based analysis (Lee & Kim, 2015; Talmage, 2020; Kofinas & Chapin, 2009) and could form the basis for analyzing carbon dependence within a unique context like remote northern communities.

The absence of a standardized notion of carbon dependency also obstructs direct comparisons of findings and the ability to synthesize knowledge across different studies. When a widely used concept has a range of interpretations, it becomes challenging to derive coherent insights that can inform evidence-based policy and decision-making. For instance, an examination of carbon dependency could consider the impacts of carbon consumption on welfare outcomes (e.g., Fang, 2011; Jacal et al., 2022). Conversely, an analysis of dependency could also consider the implications of variations in carbon prices on economic productivity, among many other investigative avenues (e.g., Houet al., 2021; Ren & Dong, 2018; Vergara, 2018). However, without a clear definition, a rationale for the selection of specific variables, and a robust conceptual framework that reflects the multidimensional nature of carbon dependency, the selection of indicators may lack a coherent justification (e.g., Hou et al., 2021; Zhang & Zhou, 2018). As a result, policy initiatives based on a narrow interpretation of carbon dependency may overlook critical factors contributing to a region's carbon dependency, resulting in interventions that address only a portion of the problem.

Finally, results reveal no scale-appropriate guidance on measuring the magnitude of carbon dependency at the community scale. Context matters at the community level, especially considering the unique influences shaping carbon dependence across communities. For example, in remote communities, economic factors such as the availability of local resources (capital, local capacity, and natural resources) and employment tied to carbon-intensive industries all together play significant roles in shaping carbon use and production patterns and limiting clean energy transition opportunities (Bridge et al., 2013; ICE, 2022; IEA, 2022; Mertins-Kirkwood, 2018; Pearce et al., 2010). Sociocultural factors, including local values, beliefs, and community practices, are also important factors driving carbon consumption patterns. For example, Sovacool and Griffiths (2020) revealed how cultural barriers influence carbon reduction and transitions in 28 countries and the need for policies to align with existing cultures and values within a community. The institutional factors (political structures and policy arrangements, energy markets, and regulatory regimes) that have been found to reinforce dependency patterns at the macroscale in Acevedo& Lorca-Susino (2021); Evans (2008); Fang (2011); Solingen (1991) may not have the same level of influence at the community level.

Quantifying the magnitude of carbon dependence across communities can provide policymakers with the basis for evaluating how different communities perform and used to support low-carbon development (Zhang & Zhou, 2018). Across the world, there are stated national ambitions to reduce dependence on fossil fuels at the community level (IEA, 2017). However, there is a need to have a multidimensional framework to assess which communities are most dependent on fossil energy. It is unclear how best to comprehensively compare communities based on the magnitude of dependency when there is a need to prioritize energy development resources across a set of communities. This form of evidence-based decision-making measurement system requires a nuanced understanding of the unique sensitivity of each community to changes in carbon availability. The variables that would serve as inputs to such a measurement framework at a macroscale may not translate to community-level assessment without adjustment for local dynamics. For instance, well-being is an essential component of community development, and energy systems support well-being actualization (Li & Chen, 2021). The dimensions of well-being can vary significantly across different spatial scales (Liu & Wu, 2021). Suppose we aim to assess the magnitude of community carbon dependency by examining well-being sensitivity to changes in carbon input; it is important to identify the aspects of well-being that are most relevant at the community level. Creating a suite of indicators while considering local factors is necessary to build a suitable community-appropriate measurement framework.

2.5 Conclusion

Through this analysis, it has been revealed that existing conceptualizations of carbon dependency within energy systems are largely inconsistent. Similarly, a standardized scale-independent definition and measurement system for understanding its magnitude has not been established. The need for a standardized definition to guide the development of a scale-dependent measurement methodology for assessing carbon dependency within remote communities has been identified. This process will involve the identification of specific community-relevant indicators to measure and an approach for aggregating data.

The limited study sample size that was deemed relevant to this analysis, despite the broad and rigorous search filter adopted, highlights the scarcity of critical analysis on carbon dependency in the literature, especially given its popularity and significance in climate change policy discussions. This disparity suggests the need for more comprehensive scholarly attention to the concept. Future research could broaden the search terms to include other implicit notions of carbon dependency, particularly considering its usage in various other languages.

Chapter 3: Energy system carbon dependence indices for remote northern communities

3.1 Introduction

The literature review from the previous chapter reveals two key findings regarding the understanding of carbon dependency. First, the existing literature lacks a consistent conceptualization and a standardized, scale-independent definition of carbon dependency, which has contributed to inconsistencies in its measurement. Additionally, the literature predominantly focuses on global, national, and regional scales, leaving a gap in the understanding of how to measure carbon dependency at the community level. To address this gap, this chapter proposes a scale-dependent measurement framework for assessing the magnitude of carbon dependence within remote northern communities.

To present a quantitative measure of carbon dependency, it makes sense to begin by defining the dependent and independent variables. Identifying context-appropriate variables for measurement lays the groundwork for modelling functional relationships. The proposed measurement framework introduced in this chapter employs well-established techniques for defining dependence indices as elasticities—fractional changes in dependent variables due to fractional changes in independent variables. Specifically, community well-being is employed as the dependent variable because choices in carbon utilization are influenced by the need to maintain conditions that enable the realization of well-being at the community level (Li & Chen, 2021). As an intermediate step, key well-being drivers are introduced to capture local community preferences regarding the conditions that contribute to their well-being levels. The most obvious choice for the relevant set of independent variables is the amounts of various fuels consumed within the community. The direct use of these quantities as independent variables introduces technical problems in the definition of dependence indices, which, in turn, complicates their interpretation. Fortunately, a simple transformation circumvents these problems and leads to easily interpretable indices.

The elasticity-as-index approach was adopted to mirror established notions of dependency in physical sciences and mathematics, where dependency measures are used to assess the degree of sensitivity of a dependent variable to changes in an independent variable. When constructing an index system, it is common practice within the literature to select a set of indicators based on expert opinion and an aggregation methodology for deriving a numerical value that explains a complex concept (Greco et al., 2019). The approach presented in this thesis generates indices that reflect the sensitivity of community subjective well-being to changes in carbon-based fuels. These indices are not merely composite values derived from some input variables; they carry a clear and specific meaning—a measure of communities perceived impact on well-being due to changes in the quantity of available carbon-based fuels. The choice of the dependent variable also requires a subjective assessment of change. While various methods exist to measure well-being levels, it is a well-established principle to adopt subjective indicators for gathering the necessary data for well-being evaluation (Michaelson et al., 2012). The carbon accounting approach adopted is based on an ideal energy system of a remote northern community. Carbon emissions are estimated from direct energy usage within the community and indirect emissions from fuel imports into the community.

Remote northern communities often experience unplanned changes in the quantity of available fossil fuels required for powering energy-based services (Kolker et al., 2022). Fuel shortages can result from various events, such as weather-related events that lead to logistical challenges in fuel delivery or other transportation issues that could result in a change in the ideal quantity of fuel required by communities. During these moments of change in fuel quantities, the operations of essential energy services may be limited, affecting critical infrastructure needed to maintain well-being conditions in the community. The proposed measurement framework helps to identify the drivers of community well-being that are most sensitive to changes in fuel quantities while also incorporating households' perceptions of change in their well-being levels. The carbon dependence indices computed by fuel type can be used within an assessment to understand priorities for interventions designed to support energy security at the community level.

The proposed framework generates a local measure of the magnitude of dependence on carbon-based fuels. This measure is theoretically and practically distinct from global carbon impact measures like the Social Cost of Carbon (SCC), which assesses global damages of carbon emissions using dollar estimates (Clarkson & Deyes, 2002). The SCC is designed to inform global climate change policies by quantifying the long-term costs of CO_2 emissions to guide investments in emission reduction (Pearce, 2002). In contrast, the dependency indices specifically assess how changes in fuel quantities available for consumption impact the perceived well-being of communities as a way of understanding local dependency on some carbon-emitting fuel sources.

While the SCC provides a macroeconomic perspective on the cost of carbon consumption, it lacks the ability to comprehensively assess the extent of dependence on specific fuel types, which is essential for addressing community-scale energy challenges. The sensitivity-based approach adopted in the computation of dependency indices allows for a nuanced understanding of how changes in fuel quantities affect key well-being drivers specific to each community, making it a valuable tool for informing sustainable energy solutions tailored to the needs of carbon-dependent communities.

This chapter is organized as follows: Sections 3.2 and 3.3 present the rationales behind the choice of independent and dependent variables, respectively. Sections 3.4 and 3.5 provide foundational knowledge of the approach adopted in building the measurement framework and the model used for evaluation. Sections 3.6 and 3.7 present guidance on what to measure when applying the framework, while Section 3.8 outlines a hypothetical scenario for applying the framework. The discussion section presents some limitations in the measurement framework and potential adaptations for future work.

3.2 CO_2 emissions attributable to local fuel consumption as independent variables

Carbon dioxide (CO_2) emissions from local fuel utilization are treated as an independent variable by quantifying all direct and indirect energy use in CO_2 equivalents. The set of carbon sources that are of interest in this analysis includes emissions from direct consumption of non-renewable, carbon-based fuels (e.g., coal, gasoline, and natural gas); renewable, carbon-based fuels (e.g., biofuels), and emissions associated with the transportation of these fuels to the community. Accounting for the carbon contributions from direct energy use and fuel transportation emissions is particularly important for remote communities that typically depend on some transportation system to import fuel into the community (Touchette et al., 2017).

CO_2 emissions estimate is used to ensure a standardized measure of carbon consumption across different fuel types. This is particularly important when aggregating fuel quantities from multiple sources; for example, aggregating the quantity of diesel used for local consumption with quantities of jet fuel used to transport diesel into the community. Using CO_2 equivalents provides a homogeneous way to compare and sum up these different types of fuels to understand total consumption, as it normalizes their contributions based on their carbon emissions from consumption rather than their physical volumes.

This analysis conceptualizes the community as a 'black box'; it is assumed that what determines a community is given and not a matter of analysis in this research. This approach focuses not on the factors that define the internal structure of a community but rather on the relationship between inputs (carbon-based energy sources) and outputs (community well-being). By abstracting the community in this manner, we examine how changes in carbon inputs influence overall community well-being. The magnitude of carbon dependence—quantified using the carbon dependency index—in a community is derived by aggregating individual household dependencies.

Consumer-level choices drive the utilization of resources. For example, gasoline-powered cars and propane-fired heating systems are produced because consumer demand exists for these products. There are implications of changes in consumer utilization of resources on transportation requirements for bringing resources into the community. As a result, it makes sense to adopt a consumer-based carbon accounting methodology where the carbon footprint of direct consumption of goods and services and indirect emissions, such as carbon emission released due to transportation to the point of use, are apportioned to the end consumer.

Given that a remote community utilizes $K + 1$ non-renewable carbon-based fuels, henceforth referred to simply as fuels, transported into the community from external sources for local consumption. Let:

$$S' = \{t, s'_1, s'_2, \dots s'_k\} \qquad \text{(Eq. 3.1)}$$

denote the CO_2 equivalent masses of these fuels where t is the fuel used for the primary mode of transportation of fuels meant for community consumption. Some remote communities also utilize electrical power supplied by a transmission grid fed by generators driven by one or more of the same fuels. It is important to note that the set S'contains readily measurable quantities whose values can, in principle, be affected by choices of consumers within the community. The total carbon footprint of the community can be expressed as:

$$G' = t + \sum_{i=1}^{K} s'_k + s_{K+1} \qquad \text{(Eq. 3.2)}$$

Where s_{K+1} represents the CO_2-equivalent mass attributable to the utilization of power from grid-attached generators. The requirement for transportation of fuel for local consumption and utilization of fuels for feeding an electrical grid introduces both conceptual and technical complications. One such complication is that changing the utilization of one fuel may indirectly affect the fuel needed for transportation.

This coupling can be eliminated by introducing a new variable, s_0, to represent the utilization of t for all purposes apart from the transportation of fuels and rescaling the remaining variables to account for the emissions produced during transportation into the community. In mathematical terms, this amounts to a linear transformation:

$$s_0 = t - \sum_{i=1}^{K} \varepsilon_k s'_k \qquad \text{(Eq. 3.3)}$$

$$s_k = (1 + \varepsilon_k) s'_k \qquad \text{(Eq. 3.4)}$$

for $1 \leq k \leq K$,where $\varepsilon_k \geq 0$. The ε_k term is the transportation factor for the fractional increase in emissions due to fuel imports. All further modelling efforts will be expressed in terms of the elements of the new set, S, below:

$$S = \{s_0, s_1, s_2, \dots, s_k, s_{k+1}\} \qquad \text{(Eq. 3.5)}$$

Before the transformation, the primed variables, S', lacked orthogonality; they were not entirely independent and had coupling effects within the analysis plane. The transformation introduces orthogonality among the variables, uncoupling each variable and ensuring that each independently contributes to understanding the total carbon footprint within a community. This transformed set of variables offers some advantages over the original primed set. First, it separates the different elements of the carbon footprint of a community, reflecting values connected to consumer choices. Second, it provides a complete set, accounting for all fuel utilization related to local community carbon emissions. The total carbon footprint can be expressed in terms of the newly transformed set:

$$G(s_0, s_1, s_2, \dots, s_K) = s_0 + \sum_{i=1}^{K} s_K + s_{K+1} \qquad \text{(Eq.3.6)}$$

3.3 Community well-being as a dependent variable

Well-being can be evaluated by understanding how people perceive the experiences that enable them to function and the extent to which they can choose the lives they value (Michaelson et al., 2012;Gaertner, 1993). Wiseman & Brasher (2008) define community well-being as: "the combination of social, economic, environmental, cultural, and political conditions identified by individuals and their communities as essential for them to flourish and fulfill their potential." For this analysis, well-being is represented using a utility function, a mathematical representation of preferences and satisfaction derived from some drivers required by households to achieve well-being outcomes(Rigoberto & Daza, 2004). Community well-being could be expressed as a social well-being function, a rule that aggregates stated well-being levels as evaluated by each household (Kakwani & Son, 2016). Given that community well-being is increasing in each individual household well-being, and some drivers of well-being mapped as $c = [c_1, c_2, \dots c_m]$. The drivers of well-being, as used here, refer to the conditions that influence how people perceive their well-being levels. If each household-stated well-being levels are defined as $H_n(c)$. Therefore, the well-being levels of N households is:

$$U = \sum_{n=1}^{N} P_n H_n(c) \qquad \text{(Eq. 3.7)}$$

Where the $\boldsymbol{P_n}$ term is the number of people within each household.

Using a well-being-based approach for the assessment of carbon dependence is not common in the current literature. Only one of the reviewed studies from the previous chapter, Thombs (2022), employed a well-being-based methodology in carbon dependence measurement. In Thombs (2022) evaluation of changes in fossil fuel production and consumption patterns on well-being, the selected variables employed for assessing carbon dependence were based on the mining sector and the study considered macroeconomic dimensions of dependence.

Across many remote and rural communities, the limited opportunities for local energy production result in a high reliance on imported fossil fuels for the preservation of conditions necessary for community well-being (Halseth et al. 2019). Therefore, it is important to incorporate this reliance on fossil fuels for well-being actualization in evaluating carbon dependence within this context. In this analysis, households are considered the basic unit for understanding the overall well-being conditions across communities because of the variation in preferences underlying perceived well-being. Subjective notions of well-being are adopted; each household is presented with a range of well-being drivers established in the literature to identify preferences.

In any given community, some well-being drivers may be connected to specific community-shared infrastructure, such as public health services and education infrastructure. While some drivers may be specific to individual households. Changes in the quantity of available fuel for shared infrastructure to utilize can have a cooperative effect, affecting the ability of the community to access services required to actualize well-being. For instance, a reduction in the quantity of fuel available for healthcare facilities or schools to utilize would limit operational capacity and affect community access to the services provided by these facilities. To capture these effects across the entire community, data would ideally be collected at two levels: at the household and community-shared infrastructure levels. In this analysis, well-being is assessed for each household using standardized surveys that capture subjective perceptions of life satisfaction. People with high levels of well-being generally perceive their lives to be going well and feel they have what is needed to function on a day-to-day basis(Stoll et al., 2012). Changes in well-being states are measured based on households' perceptions of their ability to maintain overall functionality when presented with a change scenario.

3.4 Partial derivatives as measures of dependence

Mathematically, a system of functions exhibits dependence property when there is a well-established relationship among the values of the functions (Kudryavtsev, 2020; Newns, 1967). This extends beyond simple linear functional relations to more complex systems of functions. Partial derivatives appear in many multivariate calculus texts as tools used within an assessment of dependence properties in a system of multivariate functions (Loomis & Sternberg, 1990). Partial derivatives evaluate the first-order effect of a change in a dependent variable in response to infinitesimal changes in an independent variable while holding all other independent variables fixed. As shown in figure 2 below, partial derivatives can be viewed as the slope of the surface

$f(x, y)$ at a specific point when other independent variables are held constant. The partial derivative, $\frac{\partial f}{\partial x}$ at the point (a, b), corresponds to the slope of the tangent line in the figure below.

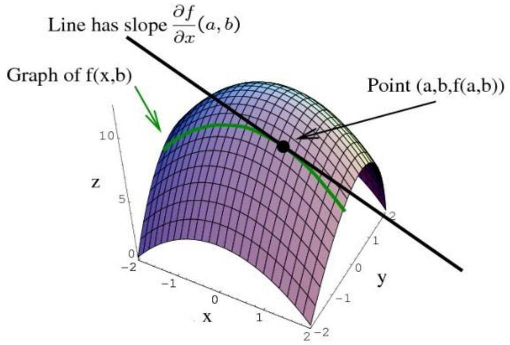

Figure 2.1: Graphical representation of partial derivatives (Nykamp DQ, n.d.). The three-dimensional surface is defined by $f(x, y)$*. At the point* $(a, b, f(a, b))$ *the tangent line in the* x*-direction has a slope given by the partial derivative* $\frac{\partial f(a,b)}{\partial x}$*, representing the rate of change of* $f(x, y)$ *as* x *varies while* y *is held constant at* b*. This partial derivative is a new vector function over the curve that indicates the direction and magnitude of the steepest gradient in the* x*-direction at the given point. This is also similar for* $\frac{\partial f(a,b)}{\partial y}$*, which measures the rate of change of* $f(x, y)$ *as* y *varies while* x *is held constant at* a*, providing another vector function that represents the slope of the tangent line in the* y*-direction. Together, these partial derivatives describe how the function* $f(x, y)$ *changes in response to variations in each independent variable.*

When dealing with functions defined by empirical data, employing finite difference approximation of partial derivatives is useful (Chapra & Canale, 2015). This method approximates the partial derivatives of a function with respect to its variables by evaluating how slight changes in one input variable affect an output quantity while keeping other independent variables constant. The finite difference approximation incrementally analyzes the changes in the output of a function as its input variables are changed by small amounts. Consider a multivariable function $f(x_1, x_2, x_3, \dots x_n)$, to approximate the partial derivative of f with respect to one of its variables, say x_1; two points x_1 and x_1+Δx_1 that are close will be selected, where Δx_1 represents a minor increment. We would evaluate the function at these points while keeping the other variables fixed and then compute the ratio of the difference in function values to the increment in the variable:

$$\frac{\partial f}{\partial x_1} \approx \frac{f(x_1+\Delta x_1, x_2, \dots, x_n) - f(x_1, x_2, \dots, x_n)}{\Delta x_1} \qquad \text{(Eq. 3.8)}$$

As Δx_1 approaches zero, the approximation on the right-hand side approaches the exact value on the left. In economics, for instance, where explicit functional relationships between variables like capital, land, and price are often unknown, economists would present the existence of an implicit function $f(W, a, b, x, y, z) = 0$; where W may represent an output such as well-being, a and b may represent functions symbolizing the factors influencing well-being, potentially dependent on variables $x, y,$ and z. Through finite difference approximations, we can investigate how changes in input variables—labour, price, and fuel—impact well-being, even without knowing the equation for W.

3.5 Defining carbon dependence indices

In this section, some principles introduced in previous sections will be employed to develop indices that reflect the magnitude of dependence by fuel type utilized within the community. The index for each fuel aggregates household-level dependencies and is calculated by evaluating the potential impact on household-stated well-being levels using a range of fuel change scenarios.

Well-being drivers linked to the functioning of community-shared infrastructure are denoted in equation 3.9 below as V. These could include infrastructure connected to education, health, etc., all of which may require fuel for ongoing operations. The well-being levels of individual households, H_n, may depend on the well-being drivers pursued during everyday activities, which may also have energy requirements satisfied by the utilization of fuels. For example, efforts to secure food may involve the use of vehicles for hunting and fishing; these vehicles may depend on fuel. The preference for well-being drivers may vary among households and can be aggregated over some N households within the community, where the number of individuals in a household is P_n. At a basic level, the community well-being function could be written as follows:

$$W = \overbrace{V(s_1, s_2, \dots, s_K)}^{\text{Collective infrastructure}} + \sum_{n=1}^{N} P_n \underbrace{H_n(c_1, c_2, \dots, c_m)}_{\text{Per household}} \qquad \text{(Eq. 3.9)}$$

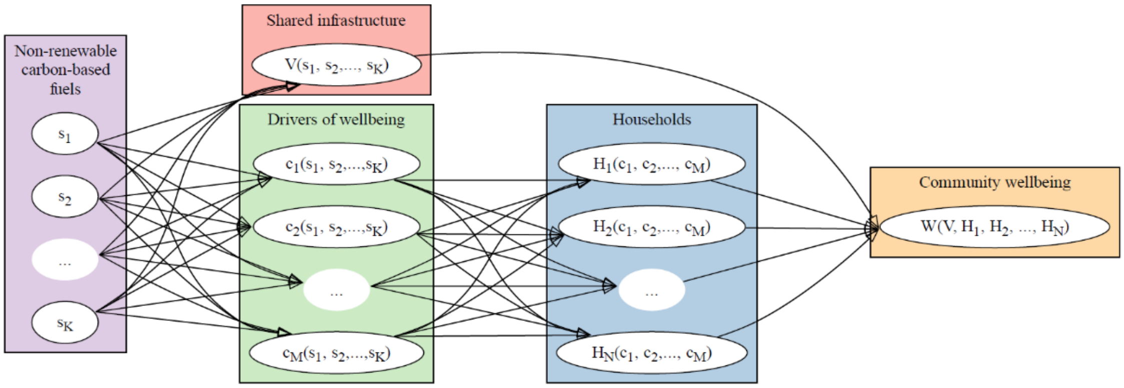

Figure 2.2: The chain of variables connecting fuel utilized within the community and community well-being. This diagram illustrates the interaction across some input variables; showing how the use of non-renewable carbon-based fuels links to drivers of well-being that are unique to individual households and those connected to shared community infrastructure. The overall community well-being is a function of these inputs, while also integrating the variances in household well-being choices. The H_n term represents the stated well-being levels mapped by households.

where $C = \{c_1, c_2, \dots, c_m\}$, is the set of well-being drivers relevant to the community. These well-being drivers represent prerequisites for individuals, households, and the community to achieve well-being. Similarly, they play an important role in simplifying the design of household-level surveys. Figure 3 visually represents the interaction across variables within the evaluation framework, which is important for understanding the chain of effect when estimating the overall change in well-being as the fuel quantity, serving as an input variable, is changed.

The community well-being term is an extensive quantity because it is additive across different components of the community system and its value is directly related to the size or scale of the system. As stated in the categorization in Chapter 2 of this thesis, there are two important properties connected to the state and size of a system: the intensive properties, which define the state of a system independent of its size, and the extensive properties, which are dependent on the size of the system.

From equation 3.9, the community-shared infrastructure term is considered an explicit function of fuel quantities. On the other hand, the household term is an implicit function of fuels. This is because changes in the quantity of fuel available to the community directly impact community-shared infrastructure, while individual household well-being levels depend on the condition of preferred well-being drivers.

To evaluate the impact of a marginal change in fuel quantity on overall community well-being, the Chain Rule is introduced here to understand the multilayered chain of effect, from the effect on well-being drivers to the unique impact on household well-being levels. The chain rule provides a model for following the chain of effects across the arrows in Figure 3.

The chain rule is a fundamental theorem in calculus for deriving the total derivative of a composite function with respect to some independent variable. For a composite function, W, that depends on intermediary variables, c_m, which is also a function of an independent variable s_k; the total derivative of W, with respect to s_k is the sum of the products of the derivatives of W with respect to c_m and the derivatives of c_m with respect to s_k (Diener & Biswas-Diener, 2002). As an analogy for understanding the chain rule, if the total cost of owning a car is the function of interest. This total cost may be affected by many factors, such as the cost of the car itself, insurance rates, fuel prices, and maintenance expenses. Each of these factors, in turn, is also affected by other variables. For instance, the fuel cost could be influenced by global oil prices, the fuel efficiency of the car, and driving frequency. If we are interested in how global oil prices ultimately affect the total cost of owning a car, we must consider the chain of effects across these variables. Using the chain rule, this would mean evaluating how changes in oil prices affect consumer behaviour (people could prefer to drive less due to this change in oil prices) and how changes in consumer behaviour affect the total cost of owning a car.

To calculate how a marginal change in fuel quantity s_k (measured in total emissions equivalent) impacts W, we would consider its direct impact on the operational capacity of each community-shared infrastructure, $\frac{\partial V}{\partial s_k}$; impact on key drivers of well-being $\frac{\partial c_m}{\partial s_k}$; and effect of change in drivers on household-level well-being, based on stated preferences $\frac{\partial H_n}{\partial c_m}$. The chain rule is used to derive the total effect at the community level, aggregating effects across these two levels, as shown in equation 3.10 below:

$$\frac{dW}{ds_k} = \left(\frac{\partial V}{\partial s_k}\right) + \sum_{n=1}^{N} P_n \left[\sum_{m=1}^{M} \left(\frac{\partial H_n}{\partial c_m}\right)\left(\frac{\partial c_m}{\partial s_k}\right)\right] \qquad \text{(Eq. 3.10)}$$

Equation 3.10 is the underlying model that guides the data collection process. Theoretically, equation 3.10 sums over the arrows in Figure 3, connecting input variables to the output quantity. To expand this analysis beyond marginal changes, the evaluation of the effect of non-marginal change in fuel is implemented using non-dimensional measures that remain consistent regardless of the units of input variables. Fractional changes help to produce non-dimensional measures that would be used as an approximation for understanding the proportionate change in well-being due to changes in fuel quantity. For simplicity, the partial differential terms in equation 3.10 will be defined as follows:

- $\frac{\partial V}{\partial s_k}$ is a measure of the sensitivity of community-shared infrastructure to changes in fuel quantity, henceforth referred to as ***ISCF.*** This quantifies how community shared infrastructure is impacted by changes in fuel quantity available to the community for consumption. The necessary data for calculating ***ISCF*** will be collected through engagement with facility managers across the various shared infrastructures.
- $\frac{\partial c_m}{\partial s_k}$ is a measure of the sensitivity of well-being drivers to changes in fuel quantity, henceforth referred to as ***WDFC***. This quantifies the level of change in each well-being driver due to changes in fuel quantity. The data required to derive this value will be obtained from expert opinion.
- $\frac{\partial H_n}{\partial c_m}$ is a measure of the sensitivity of household well-being levels to changes in well-being drivers, henceforth referred to as ***HWWD.*** This measure is derived by conducting pre- and post-assessments of well-being across households to evaluate changes in well-being levels due to changes in well-being drivers.

A similar approach used in deriving economic elasticity is employed in building carbon dependence indices; which is a ratio of fractional changes that approximates the changes in a dependent variable (community well-being) to changes in an independent variable (total energy-related carbon emission). The index is the percentage change in well-being resulting from a one-percent change in fuel, given that all other inputs to well-being are kept constant. Δs_k represents the change in emissions and ΔW is the resulting change in well-being. The dependence index for fuel k, can be expressed mathematically as:

$$I_k = \frac{\left(\frac{\Delta W}{W}\right)}{\left(\frac{\Delta s_k}{s_k}\right)} \approx \frac{s_k}{W}\frac{dW}{ds_k} \qquad \text{(Eq. 3.11)}$$

The index serves as a tool for understanding the magnitude of dependence on different energy sources (i.e., diesel dependence index, natural gas dependence index, etc.). The overall community dependency on fuel k, aggregates all individual household dependencies i.e. summing over arrows in Figure 3. Theoretically, the index I_k is an intensive property of the community. The fractional change in well-being and the fractional change in emissions are ratios of two extensive properties, resulting in a dimensionless ratio that describes the characteristics of a community independent of size, allowing for logical comparison across communities with different population sizes.

3.6 Well-being drivers

The drivers of well-being include external factors—such as education, and social connection—and internal factors like physical health, all of which can shape perception on well-being (Stoll et al., 2012). People can only achieve well-being when there are suitable conditions that allow for daily functioning and overall life satisfaction (Michaelson et al., 2012). Some well-being literature, e.g., O'Sullivan & McHardy (2008); Li & Chen (2021); Wiseman & Brasher (2008); Kakwani & Son (2016), have identified some drivers contributing to community well-being across dimensions such as: economic, health, social relationships, built environment, and education. The example drivers discussed below can be directly or indirectly affected by changes in the quantity of fuel available to the community for local consumption.

Social relationship

Maintaining strong social relationships enhances overall life satisfaction (Dolan et al., 2008; Pichler, 2006). Community spaces for religious, cultural, and social interaction help to create opportunities for individuals to socialize and contribute to local development initiatives. Similarly, these spaces enable community members to volunteer for causes that interest them. According to Meier & Stutzer (2008) and Wheeler et al. (1998), such volunteering activities are associated with high levels of perceived well-being. The physical spaces used to organize events that support social connection within the community could rely on some energy sources to function. When there is a change in the quantity of fuel supplied to these physical spaces, the opportunities for individuals to socialize and participate in volunteering activities could be limited.

Health

Self-reported physical and psychological health is positively associated with overall life satisfaction (Flouri, 2004; Stoll et al., 2012). Fuel shortages can impact the operations of community healthcare facilities, thereby limiting community access to essential healthcare services needed to sustain the physical health of households. Similarly, participation in physical exercise, which is positively correlated with well-being (Biddle & Ekkekakis, 2005; Dolan et al., 2008), can be restricted due to the limited operations of community gyms and exercise centers that could rely on fuel to function.

Education

Well-being surveys conducted by Hartog & Oosterbeek (1998) have found a positive association between educational attainment and subjective well-being, controlling for variables like income and health (Stoll et al., 2012). Energy plays a key role in supporting the social and psychological development activities in schools and daycares. Fuel shortages can reduce instructional hours across educational facilities and their ability to achieve quality learning outcomes.

Household living conditions

The perception of comfort within the living environment positively influences subjective well-being (Dolan et al., 2008; Guite et al., 2006). The quality of the built environment within a household, which significantly contributes to comfort (Dovjak & Kukec, 2019), depends on essential energy services such as electricity for household appliances, heating, and cooling. When the energy supplied to households is reduced, their ability to access these services could be directly affected, impacting overall comfort and stated well-being.

3.7 Steps for data collection and aggregation

To compute indices for a set of communities, the steps outlined in Figure 4 below will be followed for data collection and aggregation. Data would be collected at three levels: at the infrastructure level, expert level, and household level. Based on established principles within the literature for well-being evaluation, data on well-being changes would be captured through questions that explore life satisfaction at the household level (Michaelson et al., 2012). Expert assessment would be used to quantify the potential change in well-being drivers based on data collected at the infrastructure-level.

It is assumed that households are primarily concerned with reliable access to energy services and infrastructure that support their daily lives, rather than the specific quantities of fuel available to their community. Based on this assumption, the household surveys within the framework focus on understanding how well-being is affected by changes in the conditions necessary for well-being, rather than variations in fuel quantities. While fuel availability impacts the delivery of well-being drivers, households would, logically, be more interested in how fuel disruptions affect the quality and accessibility of the services they depend on.

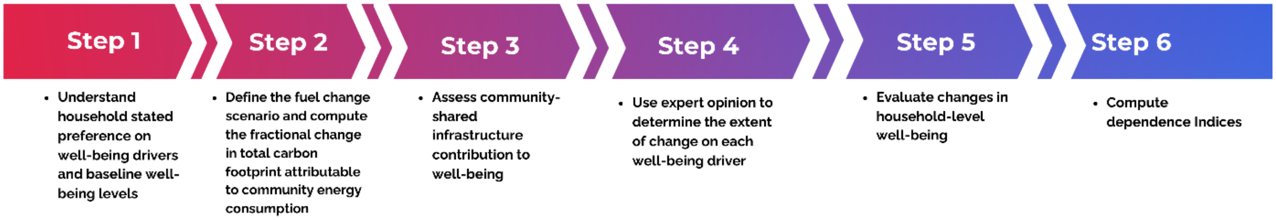

Figure 2.3: An overview of the stepwise process for computing carbon dependence indices by fuel type. This process involves data collection at the household level, infrastructure level and expert level. The main output of the data collection process is to derive the fractional change in community well-being and the fractional change in carbon emission that will be used for the computation of the carbon dependency indices.

As shown in Figure 4 above, the first phase involves evaluating stated baseline well-being levels across households and preferences on well-being drivers. The evaluator is expected to set the fuel change scenarios that will be used for assessment and work with facility and energy management representatives within the community to understand impact of the fuel change scenarios on each shared infrastructure. A before and after comparison of stated well-being will be done to evaluate changes in well-being at the household level. The steps outlined in Figure 4 are further detailed below:

Step 1: Understand household stated preference on well-being drivers and baseline well-being levels

This involves using household-level surveys to evaluate preferences on well-being drivers and subjective assessment of well-being levels. To ensure this data collection process is structured, households will be presented with a list of well-being drivers established in the literature that influence community well-being levels. A representative from each household is expected to prioritize the list of drivers in order of importance to their family and evaluate household present well-being levels by providing answers to the survey questions below:

- Please rank the following in the order of importance to your household: access to healthcare, education, social connection, suitable household living conditions. Additionally, please specify any other factors not listed that significantly contribute to the daily fulfillment of your family.
- All things considered, how satisfied are you with your life as a whole these days? Please give a score from 1 to 10, where 1 means extremely dissatisfied and 10 means extremely satisfied.

The first question is required to understand the value placed on a list of drivers and identify the top drivers per household as a requirement to evaluate ***WDFC.*** The second question serves as a baseline well-being assessment survey before households are presented with the fuel change scenario. This is a standard well-being survey from the National Economics Foundation(Michaelson et al., 2012), required to evaluate the $H_n(c)$ for each household. ***Appendix B*** shows mock survey responses and representative data required for computing indices.

Step 2: Define the fuel change scenario and compute the fractional change in total carbon footprint attributable to community energy consumption.

The objective here is to establish the fuel change scenario against which impact will be assessed and compute the total emission equivalent of this scenario. The carbon accounting principles adopted here helps to evaluate the total emissions generated locally related to energy consumption, including emissions due to the transportation of fuel needed for local consumption.

A change in the quantity of fuel imported into a community may not directly correspond to changes in fuel requirements for its transportation system, particularly if the community also imports other essential resources like food with the same transportation system. The interest here is to understand how a change in the quantity of fuel meant for local consumption affects the total carbon footprint attributable to community fuel utilization. The questions below would guide the collection of data at this stage:

- What is the average volume of fuel transported into the community weekly?

- What is the total fuel requirement for each transportation system used to import fuel and other resources into the community?
- What is the mass of other non-fuel resources transported into the community by each transportation system used?

These questions would be answered by local energy management representatives within the community. The first question in this section is required to calculate s_k' and ε_k. The second and third questions are required to evaluate the transportation requirement for fuel importation which is needed to calculate the total emission equivalent, $s_k = (1 + \varepsilon_k)s_k'$; and also the fractional change in total emissions at each fuel change scenario, $\frac{\Delta s_k}{s_k}$. See section 3.8 for an example scenario where s_k is computed.

Step 3: Assess community-shared infrastructure contribution to well-being.

The goal for this stage is to understand how changes in fuel quantity affect the operational capacity of each shared infrastructure within the community. This could include schools, health centres, social centres, etc. This data collection process would involve engaging energy management personnel and facility managers within the community using the questions below as a guide:

- What is the average fuel quantity required to support ideal operation across shared infrastructure within the community by fuel type? This could include the central power generating system, and other central energy system within the community.
- In a scenario where the community experiences a reduction (provide the fuel change quantity that will be used for analysis) in available fuel for consumption, with no immediate alternatives and assuming other factors remain unchanged, how long could each infrastructure operate?

The aim here is to evaluate the potential impact of fuel change across community-shared infrastructure, i.e. ***ISCF***. This would guide expert assessment of the level of change in each well-being driver connected to one or more of these infrastructures. See ***Appendix B*** for mock responses to these questions.

Step 4: Use expert opinion to determine the extent of change on each well-being driver

Data from the infrastructure-level surveys would inform expert opinions on the level of potential change in each well-being driver due to changes in fuel quantity. To obtain ***WDFC*** data for each well-being driver, a pre- and post-comparison would be conducted, evaluating percentage changes in the ideal state of each well-being driver against its potential state due to changes in fuel. Changes in the quantity of fuel available to a community can uniquely affect each well-being driver differently, independent of individual household preferences. The following questions could be used to guide expert assessment of change across some common community-based well-being drivers. The responses to the questions below are expressed as a % change in some units of well-being. Mock responses to these questions are outlined in ***Appendix B.***

- **Social connection:** What is the potential change in the number of community social, cultural, and religious activities due to changes in the quantity of fuel available to support the operational capacity of physical spaces used to enable social connection?
- **Health:** What is the potential change in the number of medical procedures that community health centres could deliver due to changes in the quantity of fuel available to support the ideal operations of health facilities within the community?
- **Education:** What is the potential change in the instructional hours available to community learners due to changes in the operational capacity of schools and daycares?
- **Household living conditions:** What is the potential change in the number of hours that households can access energy services due to the reduced operations of central community electric power generators and heating systems?

Step 5: Evaluate changes in household-level well-being

The effect of changes in well-being drivers could differ for each household based on the perceptions of impact on well-being levels. At this stage, we will use life satisfaction surveys—the most common measure of well-being in the literature (Stoll et al., 2012)—to evaluate changes in subjective well-being when presented with a well-being driver change scenario. Given that each household representative was presented with the potential change scenario across each driver, the following are some example surveys connected to each well-being driver:

- Given this change in your household participation in community social and cultural events, how satisfied are you now with your ability to achieve daily fulfilment?
- Given this limited access to healthcare services, how satisfied are you now with your ability to achieve daily fulfilment?
- Given this change in the instructional hours available to members of your household, how satisfied are you now with your ability to achieve daily fulfilment?
- Given this change in the number of hours that your household can operate energy services, how satisfied are you now with your ability to achieve daily fulfilment?

For each question above, the household representative serving as the survey respondent is expected to provide a score from 1 to 10, where 1 means extremely dissatisfied and 10 means extremely satisfied. To compute $\boldsymbol{HWWD}$, the difference between the baseline well-being score (from Step 1) and the current well-being levels would be calculated for each household. See ***Appendix B*** for mock survey responses to these questions.

Step 6: Compute dependence indices

The dependence index, I_k, for a fuel type, *k*, as provided in equation 3.11, is the ratio of overall fractional change in community well-being to the fractional change in CO_2 equivalent emissions for each scenario. The overall change in community well-being is derived by aggregating the product of $WSFC$ and $HWWD$, i.e. $\Delta W = \sum_m^M \sum_n^N P_n(WSFC_m \times HWWD_n)]$ for each household. See ***Table 1*** for a summary data table and computation of the diesel dependence index for a hypothetical community. ***Appendix B*** includes all the data used for the index computation.

3.8 Example scenario

The evaluation framework is applied to measure diesel dependence using hypothetical community data and a fuel change scenario (10% reduction in fuel quantity). To simplify the analysis, we assume the following:

- The hypothetical community has only two households: household A has 3 members (i.e. $P_n = 3$), and household B has 5 members (i.e. $P_n = 5$).
- Each household has the same preferred list of well-being drivers (c_1–c_4) and values them equally, as shown in Table 1.

- There are 5 shared infrastructures within the community; mapped as V1–V5 in ***Appendix B.***

Appendix B shows the hypothetical data with mock responses from surveys conducted at the infrastructure level, expert level, and household levels.

To get the fractional change in emissions for this fuel change scenario, the ε_k term, which is the transportation factor that accounts for the additional emission associated with transporting fuel into the community introduced in equation 3.4, will be derived. This term will be used to derive the total (direct and indirect) emission for the different fuel change scenarios.

Given that the ideal volume of diesel flown into the community is 5000 litres per week, and the airplane used to import diesel into the community consumes 300 litres of jet fuel per week. The standard CO_2 emission factor for diesel fuel is approximately 2.68 kg CO_2 per litre of diesel (Environment and Climate Change Canada, 2024). The s'_k = 5000 litres of diesel × 2.68 kg CO_2 per liter of diesel = 13400 kg of CO_2. The standard emission factor for jet fuel is about 3.15 kg CO_2 per litre of jet fuel burned (International Air Transport Association, 2022). The transportation emission due to diesel importation = 300 litres x 3.15 kg CO_2 per litre = 945 kg of CO_2. For this community, the transportation-related CO_2 emission coefficient, ε_k for diesel is:

$$\varepsilon_k = \frac{945}{13400} = 0.07$$

This value indicates how much additional CO_2 is emitted through the transportation system per litre of diesel transported. Recall that: $s_k = (1 + \varepsilon_k)s'_k$. Therefore:

$$s_k = (1 + 0.07)13400\ kg\ of\ \mathrm{CO_2}$$

$$s_k = 14{,}338\ kg\ of\ \mathrm{CO_2}$$

For a 10% change in the volume of diesel flown into the community, s'_{k10} (at the 10% reduction scenario) becomes 12060 $kg\ of\ \mathrm{CO_2}$.

$$s_{k10} = (1 + 0.07)12060\ kg\ of\ \mathrm{CO_2} \approx 12904\ kg\ of\ \mathrm{CO_2}$$

The fractional change in total emissions at this scenario is $\frac{\Delta s_k}{s_k} = \frac{14338-12904}{14338} = 0.1$

Table 1: Summary data table showing the computed WSFC per well-being driver and HWWD per household. The values are from the comprehensive data table in ***Appendix B,*** showing mock responses to surveys delivered at the household level, expert level and infrastructure level**.** The overall change in community well-being is computed using the summation of the product of *WSFC and HWWD* computed by households.

		HWWD	
Well-being Driver	**WSFC**	**Household A: P_n = 3 people**	**Household B: P_n = 5 people**
c_1: Social connection	0.3	0.125	0.33
c_2: Health	0.15	0.5	0.5
c_3: Education	0.15	0.25	0.167
c_4: Household living conditions	0.1	0.625	0.5

This hypothetical case considers discrete changes in well-being drivers and household well-being levels. The values for WSFC and HWWD are derived from mock survey responses (see Appendix B) based on expert assessments of change in well-being drivers and household-level assessments of changes in their well-being levels, respectively. For example, the WSFC value for the well-being driver, 'c1: social connection', was derived from the response: 'Due to changes in the operational capacity of community physical spaces, the number of social, cultural, and religious activities will decrease by 30%.' This 30% decrease in well-being drivers is expressed as 0.3 in well-being units.

To derive the HWWD term, we compared survey responses from the baseline evaluation (before the change scenario) with responses after presenting households with a potential change scenario. At the baseline, households were asked, 'All things considered, how satisfied are you with your life as a whole these days? Please give a score from 1 to 10, where 1 means extremely dissatisfied and 10 means extremely satisfied.' To assess changes in well-being due to the fuel change scenario, households were asked—'Given this limitation in your ability to participate in social networks, how satisfied are you now with your ability to achieve daily fulfillment? Please give a score from 1 to 10, where 1 means extremely dissatisfied and 10 means extremely satisfied'—the difference between their well-being scores before and after the change scenario was used to calculate the HWWD value. All values are expressed in well-being units to ensure ease of aggregation (See Appendix B for the complete data table).

$$\Delta W = \sum_{m}^{M} \sum_{n}^{N} P_n(WSFC_m \times HWWD_n)] = [3((0.3 \times 0.125) + (0.15 \times 0.5) + (0.25 \times 0.15) + (0.1 \times 0.625))] + [5((0.3 \times 0.33) + (0.15 \times 0.5) + (0.15 \times 0.167) + (0.1 \times 0.5))] = 1.24525 + 0.6375$$

$$\Delta W = 1.8825$$

$W = \sum_{n=1}^{N} P_n H_n(c) = [(3\times0.8) + (5\times0.6)] = 5.4$ (H_n values are from the baseline well-being surveys from Table B.2 within Appendix B)

$$\frac{\Delta W}{W} = 0.35$$

Diesel dependence index for this community at the 10% diesel reduction scenario =

$$I_k = \frac{\left(\frac{\Delta W}{W}\right)}{\left(\frac{\Delta s_k}{s_k}\right)} \approx 3.5$$

For this point estimate, if other factors that influence well-being remain constant, a 1% decrease in diesel quantity corresponds to a 3.5% decrease in community perceived well-being levels. It is important to note that this measure assumes that other contributors to well-being are unchanged in the evaluation scenario, isolating diesel quantity as the only changing input variable in this context.

To rank a set of communities using this framework, a set of diesel change scenarios would be evaluated using the same step outlined in Section 3.6. Similarly, in these fuel change scenarios, communities may allocate the distribution of available fuel differently across each infrastructure. The allocation strategy adopted by each community may determine the level of impact across each driver.

3.9 Discussion

The proposed framework incorporates households' perceived notion of change into the index computation process and evaluates the sensitivity of well-being drivers unique to each community. Based on the hypothetical scenario, community social connection would experience a relatively higher impact, suggesting a high degree of vulnerability to changes in diesel quantity. On the other hand, the impact on household living conditions is lower, indicating lower sensitivity to diesel changes. This community-based approach ensures that the generated indices reflect the unique realities of each community, as assessed by those who directly experience the dependency being evaluated.

The quality of this evaluation could be further improved by adopting a range analysis, using a range of fuel change scenarios to assess potential effects on community well-being. The same principle adopted to derive the point estimate within the hypothetical scenario would be used. Statistically, single-point estimates are unlikely to reflect the true magnitude of carbon dependence. Using a set of distinct fuel change scenarios helps develop a distribution of potential impacts on community well-being. The shape and characteristics of this distribution improves the likelihood of accurately assessing the magnitude of dependence.

The functional form of the community well-being function would influence the elasticity estimates generated. As outlined in Greer (2012), a linear functional form assumes a constant marginal effect, a log-linear form would have a constant percentage change, yielding a consistent elasticity estimate. Similarly, the Cobb-Douglas[2] form provides constant elasticity derived directly from its exponents, while a quadratic form allows for non-linear interactions, resulting in elasticity that changes with the values of the variables. Theoretically, the choice of the functional form should be based on the best fit with the data collected from the community.

Depending on the scale of analysis, this framework could also be applied using some other dependent variable. For instance, we could conceptualize community livelihoods (defined in DFID (1999) as the capabilities, assets, and activities necessary for sustaining living conditions) as the dependent variable and examine how changes in fuel quantity could impact this multidimensional concept. What is most important when selecting the dependent variables is suitability to the context of application and a clear definition of indicators for measurement. Similarly, while our focus in this analysis has been on carbon emissions equivalents as an independent variable, the conceptualization of "carbon" in a different scale of analysis could be carbon price. This was applied in two of the reviewed studies in Chapter 2—Acevedo & Lorca-Susino (2021) and Benedictow et al. (2013). Using carbon price as an independent variable could be more relevant in macro-scale analysis, where the impact of changes in energy prices is more noticeable. However, in remote northern communities, the changes in energy prices often do not directly reflect at the community level due to national and provincial subsidies (Pembina Institute, 2021a). In remote community contexts, focusing on carbon emission estimates is more useful in understanding the magnitude of dependence because we can easily evaluate how changes in carbon consumption choices impact a community-relevant variable like well-being.

The carbon dependence index provides a baseline assessment without considering the ability of communities to adapt in a fuel change scenario. The adaptive potential of a community, as highlighted in IPCC (2007) and Nelson et al. (2007), is reflected in their capacity to mitigate

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[2] *The Cobb–Douglas function has the form $Y = AK^a L^b$, where Y is an output function; A, a and b are positive constants, K, L could represent some input variables*(Cohen, 2014).

the adverse effects of change. This capacity for adjustment is influenced not only by the availability of resources but also by social structures in the form of local leadership and local skills (Ahmad et al., 2021; Smit & Wandel, 2006). Additionally, the ability to mobilize existing resources in fuel change scenarios could also play a critical role in community adaptation (Hill & Engle, 2013; Nelson et al., 2007).

The community well-being model does not inherently account for the potential negative effects of fossil fuel consumption, such as environmental degradation and other negative externalities related to fuel usage. The scope of the carbon dependency evaluation model intends to isolate and understand the direct impact of fuel changes on stated well-being. This approach helps delineate the positive aspects of energy access in the community without delving into the optimization of resources or environmental impacts. If the model were to be used for optimization purposes, incorporating constraints related to environmental impacts and financial costs on communities would be essential. Employing constrained optimization techniques could help identify ways to maximize well-being improvements while minimizing environmental impact and financial cost to communities. Future iterations of this study could incorporate optimization activities that include economic, environmental, and social constraints for community energy planning and resource optimization.

Furthermore, the carbon dependence indices could form part of a decision-making tool when there is a need to identify priorities in energy development interventions for reducing fossil fuel dependence across a set of remote communities. Policymakers sometimes face the challenge of resource allocation when supporting energy initiatives in multiple communities (Look et al., 2022). The indices provide an additional layer of understanding of the sensitivity of each community to changes in fuel quantity available within a community. By offering a nuanced perspective on how different communities are affected by variations in fuel availability, these indices can help guide more targeted and effective energy transition strategies.

The proposed framework offers a rigorous and theoretically sound approach for measuring carbon dependency. Although the process of data collection required for computation may seem resource-intensive, especially as the model is employed for communities with larger populations. A large variation in preferences for well-being drivers in communities with large population sizes introduces additional layers of difficulty, making it more challenging to measure and analyze carbon dependence at a macroscale using this well-being-based approach. While sampling households may be a practical solution, it could sacrifice the granularity and precision that comes from understanding preferences at the individual household level. Despite these practical challenges, the framework is grounded in logic and connects the dots across established principles in the literature**.**

3.10 Conclusion

As global commitments to reduce fossil fuel dependence become more localized, refining methods for measuring the magnitude of dependence across various contexts becomes increasingly important. While many national governments develop ambitions to shift communities towards local, renewable energy sources, these ambitions and policy development processes need to be backed by evidence on the magnitude of carbon dependence across communities. Our primary objective, to establish a conceptual framework for the measurement of carbon dependency, has been achieved. A key next step would involve applying this framework using real data across communities, working with the foundational principles presented in this chapter.

Future research could also aim to expand the scope of this work to include dimensions of adaptive capacity in a measurement of carbon dependence. This would include examining how communities perform when considering structures that facilitate adaptation in scenarios of reduced carbon utilization. Doing so will not only deepen our understanding of how communities vary in their responses to changes in carbon utilization scenarios but will also showcase the relationship between the magnitude of carbon dependence and adaptive capacity. Investigating which elements of adaptive capacity are most important to support community resilience in these scenarios of limited fuel utilization becomes even more important. By providing the foundational framework within this article, we aim to stimulate ongoing scholarly efforts that will support evaluation standards for global carbon dependence measurement.

Chapter 4: Conclusion

This study represents the first known comprehensive review of the literature on carbon dependence of energy systems and the first attempt at developing a measurement system for evaluating carbon dependence in remote northern communities. This thesis advances understanding of the concept in three distinct ways. Firstly, it unifies the knowledge production landscape, paving the way for future exploration of the concept along different dimensions. Second, the rigorous formalism clarifies the logic underlying the proposed measurement system, enhancing its potential for future application with real community data. Third, this thesis marks a significant shift in the conceptual direction of the field, promoting new perspectives on carbon dependency and introducing opportunities for developing new evaluation principles. Future studies must embrace the multidimensionality of carbon dependency and push the boundaries of the measurement variables proposed in this study. A key message from this analysis is the need to distinguish between carbon dependency and carbon utilization measures. This distinction is often overlooked in most of the reviewed studies.

Beyond its application in evaluating carbon dependency within energy systems, the proposed measurement approach is adaptable and can be employed in other systems, such as food and water systems. Although the elasticity-as-indices approach is generic, application across other systems requires thoughtful selection of suitable dependent and independent variables tailored to the specific research context. Future research could also explore output-based understanding of carbon dependence. For example, considering communities that rely on carbon-based commodities for export rather than local consumption. For these communities whose viability is tied to carbon production, changes in the quantity of carbon-based commodities produced by the community could significantly impact local economic development and livelihoods.

Regional governments aiming to support investments in fossil fuel reduction interventions across communities could benefit from the proposed measurement framework. Computing dependence indices by fuel type provides a starting point for identifying energy transition priorities across a set of communities to maximize the impact of energy investments. The use of household surveys and infrastructure-level assessments allows the measurement system to accurately capture community preferences and the contribution of local energy use to community satisfaction.

It is important for future users of the measurement framework to explore how this approach can be adapted for macroscale analysis and other local contexts. This adaptation could include determining relevant variables to be measured based on the context of the application. For example, when measuring carbon dependence in a remote African community, the factors considered as drivers of well-being could differ from those in remote northern communities. Part of the process of strengthening the internal validity of the framework is ensuring that what is measured is truly reflective of local conditions and needs.

Due to the constraints in time and resources allocated, collecting actual data from various communities was not feasible, which is essential for empirical testing of the model. Data collection is deferred to future work that aims to apply the framework across a set of communities.

Appendix A: Categorization of reviewed studies into each domain of analysis

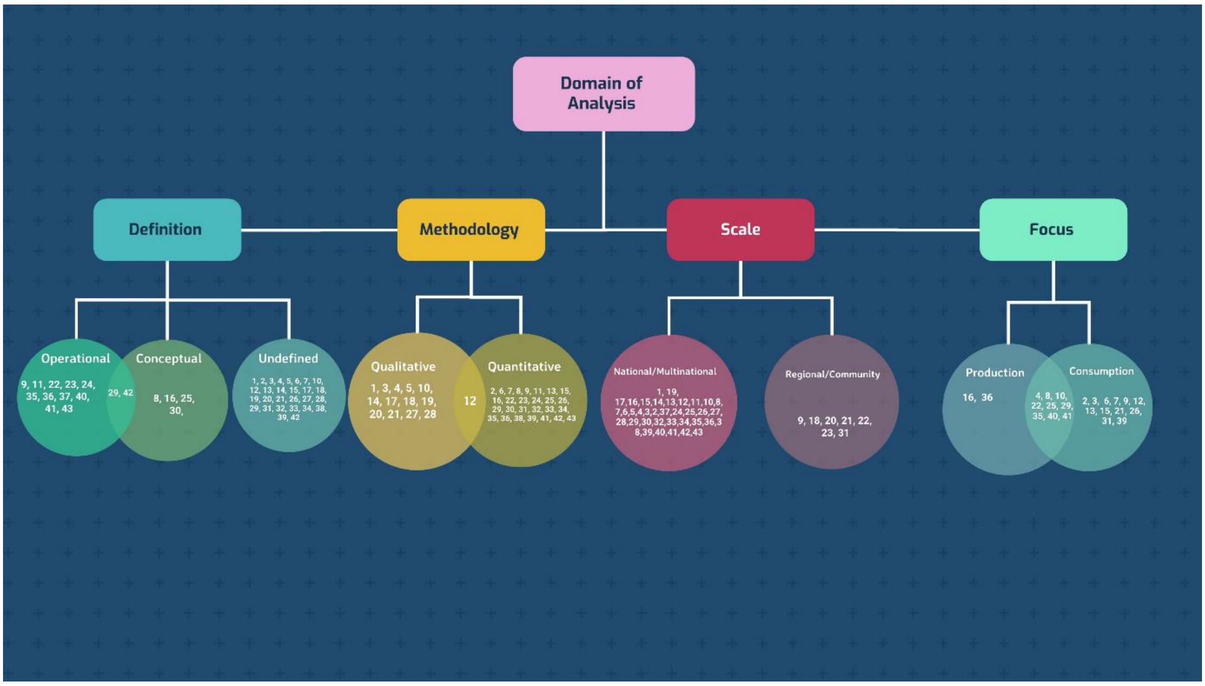

Figure A.1: Categorization of reviewed studies into each domain of analysis. Each of the sample study was reviewed along these four domains: Definition, Methodology, Scale and focus. Within each domain, studies were further categorized along operational and conceptual definitions; qualitative and quantitative methodology; national/multinational and regional/community scale; production and consumption focused analysis.

Table A.1:List of reviewed studies

Ref. No.	**Title**	**Authors**
1	Managing Energy Vulnerability: Brazil's Adjustment to Oil Dependency	Solingen, Etel
2	Economic welfare impacts from renewable energy consumption: The China experience	Fang, Yiping
3	On the economics of electricity consumption in small island developing states: a role for renewable energy technologies?	Weisser, Daniel
4	Pathways to Overcoming Natural Gas Dependency on Russia & The German Case	Halser, Christoph; Paraschiv, Florentina
5	Do indicators have politics? A review of the use of energy and carbon intensity indicators in public debates	Rodriguez, Miguel; Pansera, Mario; Lorenzo, Pablo Cabanelas

6	Modelling the global relationships among economic growth, energy consumption and CO_2 emissions	Chen, Ping Yu; Chen, Sheng Tung; Hsu, Chia Sheng; Chen, Chi Chung
7	Food security and fossil energy dependence: An international comparison of the use of fossil energy in agriculture (1991-2003)	Arizpe, Nancy; Giampietro, Mario; Ramos-Martin, Jesus
8	The impact of disaggregated oil shocks on state-level real housing returns of the United States: The role of oil dependence	Gupta, Rangan; Sheng, Xin; Van Eyden, Reneé; Wohar, Mark E.
9	Low Carbon Economy Evaluation Index System and Development Evaluation of Hebei	Wei-Yu, Wang; Nian, Yang
10	How Coal Kept My Valley Green: Forest Conservation, State Intervention, and the Transition to Fossil Fuels in Mexico	Vergara, German
11	Oil dependency of the Russian economy: An econometric analysis	Benedictow, Andreas; Fjærtoft, Daniel; Løfsnæs, Ole
12	From carbon dependence to renewables: The European oil majors' strategies to face climate change	Vieira, Leticia Canal; Longo, Mariolina; Mura, Matteo
13	Analysis of oil export dependency of MENA countries: Drivers, trends and prospects	Bhattacharyya, Subhes C.; Blake, Andon
14	Green conservatism or environmental nativism?: Exploring carbon dependency as populist political strategy in Poland	Riedel, Rafał
15	Stochastic Kaya model and its applications	Chang, In; Chang Hwang, In
16	Measuring energy security: Can the United States achieve oil independence?	Greene, David L.
17	Potential transport energy demand and oil dependency mitigation measures	T.E. Lane-Visser; Marianne Vanderschuren.
18	Transformation from "Carbon Valley" to a "Post-Carbon Society" in a Climate Change Hot Spot: the Coalfields of the Hunter Valley, New South Wales, Australia	Evans, Geoffrey R
19	The European Union oil dependency: a threat to economic growth and diplomatic freedom	Acevedo, Rafael Alexis; Lorca-Susino, Maria
20	Transition to a post-carbon society: Linking environmental justice and just transition discourses	Evans, Geoff; Phelan, Liam

21	Urban resilience in the face of fossil fuel dependency: the case of Rio de Janeiro’s urban mobility	Fernandes, Vicente Aprigliano; Rothfuss, Rainer; Hochschild, Volker; Da Silva, Marcelino Aurelio Vieira; Da Silva, William Ribeiro; Steiniger, Stefan; Dos Santos, Tálita Floriano
22	Climate change, carbon dependency and narratives of transition and stasis in four English rural communities	Phillips, Martin; Dickie, Jennifer
23	A non-compensatory composite indicator approach to assessing low-carbon performance	Zhang, L. P.; Peng Zhou
24	Towards Green and Low-Carbon Development in Chinese Cities	Chen, Meian; Yang, Li; Hu, Min; Montero, Diego
25	Implications of paradigm shift in Japan's electricity security of supply: A multi-dimensional indicator assessment	Portugal-Pereira, Joana; Esteban, Miguel
26	Have fossil fuels been substituted by renewables? An empirical assessment for 10 European countries	Marques, António Cardoso; Fuinhas, José Alberto; Pereira, Diogo André
27	Recession and fossil fuel dependence undermine climate policy commitments	Ide, Tobias
28	Fossil Fuels, GHG Emissions and Clean Energy Development: Asian Giants in a Comparative Perspective	Jain, Varinder
29	Evaluation of electricity supply sustainability and security: Multi-criteria decision analysis approach	Ren, Jingzheng; Dong, Liang
30	The carbon performance of the 100 largest US electricity producers	Busch, Timo; Weinhofer, Georg; Hoffmann, Volker H.
31	Economic costs and environmental impacts of fossil fuel dependency in sub-Saharan Africa: A Nigerian dilemma	Jacal, Samara; Straubinger, Franziska Brigitte; Benjamin, Emmanuel Olatunbosun; Buchenrieder, Gertrud
32	Fossil-fuel dependence and vulnerability of electricity generation: Case of selected European countries	Bhattacharyya, Subhes C.
33	Renewable Energy Use and Ecological Footprints Mitigation: Evidence from Selected South Asian Economies	Xue, Lian; Haseeb, Mohammad; Mahmood, Haider; Alkhateeb, Tarek Tawfik Yousef; Murshed, Muntasir
34	Aiding fossil fuel dependency: a cross-national analysis of energy sector aid, national autonomy, and CO_2 emissions in 122 nations	Henderson, Kent E.; Sommer, Jamie
35	The asymmetric effects of fossil fuel dependency on the carbon intensity of well-being: A U.S. state-level analysis, 1999–2017	Thombs, Ryan P.

36	Making decarbonization work for workers Policies for a just transition to a zero-carbon economy in Canada	Mertins-Kirkwood, Hadrian
37	Energy Indicators for Sustainable Development: Guidelines and Methodologies | IAEA	IAEA
38	Energy supply security in the EU: Benchmarking diversity and dependence of primary energy	Chalvatzis, Konstantinos J.; Ioannidis, Alexis
39	Climate Change Policies, Energy Security and Carbon Dependency Trade-offs for the European Union in the Longer Term	Kuik, Onno
40	Does Fossil Fuel Dependence Influence Public Awareness and Perception of Climate Change? A Cross-National Investigation	Knight, Kyle W.
41	Construction and measurement of China’s comprehensive energy dependence index	Hou, Xiaochao; Zhou, Jingjing; Zhang, Lei; Yang, Qing
42	Social Capital, carbon dependency, and public response to climate change in 22 European countries	Hao, Feng; Liu, Xinsheng; Michaels, Jay L.
43	The Sustainable Energy Development Index—an application for European union member states	Ligus, Magdalena; Peternek, Piotr

Table A.2: Indicators identified in seven studies that employed composite systems in evaluating implicit forms of carbon dependence

Referenced study	Hou et al. (2021)	Knight (2019)	Thombs (2022)	Chen et al. (2020)	Zhang & Zhou (2018)	Marques et al. (2018)	Raimi (2021)
Aim of study	Estimates China's dependence on four energy sources: coal, oil, natural gas, and clean energy	Investigate the influence of carbon dependence on climate change public opinion	Studies U.S. state-level fossil fuel dependency effects on well-being	Evaluate Chinese cities performance on carbon development	Assess carbon performance across Chinese cities	Evaluate fossil fuel dependency across 10 European countries considering electricity demand, capacity and generation systems.	Evaluate fossil fuel dependency across US counties, considering Economic dependence on fossil fuel
Indicators	Energy consumption/GDP Energy consumption & production growth rate/GDP Proportion of energy consumption across energy sources *Value added of tertiary industry/GDP*	Carbon intensity of energy consumption – kg of CO_2 per Kg of oil equivalent energy use Carbon intensity of economy - Kg of CO_2 emission per PPP $of GDP % of total electricity production from oil, gas and coal Fossil fuel energy consumption as a % of total energy consumption	Energy production-consumption ratio Value of fossil fuel industry export divided by the total value of all export The share of GDP coming from fossil fuel sector	Energy Intensity Carbon Intensity CO_2 emissions per capita Primary energy consumption per capita Non-fossil fuel share Industrial energy intensity Heavy industry share of industrial GDP Public transportation vehicles Urban rail extent Bus trips/capita	Energy intensity R&D expenditure to GDP Loan volume to GDP Proportion of tertiary industry Proportion of public green space Water consumption intensity Engle's coefficient Registered unemployment rate	Electricity production from coal, oil and natural gas (TWh) Electricity production from coal (TWh) Electricity production from oil (TWh) Electricity production from natural gas (TWh) Electricity production from hydro power (TWh)	Coal production per capita Economic status Bachelor's degree Rurality Share minority population Share linguistic isolation Share pre-1960 housing Air toxics cancer risk Toxic water discharges Superfund sites Ambient ozone

				Green buildings share Residential energy consumption per capita Commercial energy consumption per employee Municipal solid waste per capita Blue sky days PM2.5 concentration Water consumption per capita Environmental spending as share of city budget Green space per capita Low-carbon/climate change plan Renewable energy strategy Climate change resilience plan	Population density Days of air quality equal to or above Grade Ratio of industrial solid wastes utilized Proportion of waste water treated Ratio of consumption waste treated Public buses per capita Passengers intensity	Electricity production from intermittent RES (TWh) Installed capacity of wind power (MW) Installed capacity of solar PV (MW) Installed capacity of bioenergy (MW) Installed capacity of fossil fuels (MW) Hydro power contribution to electricity generation (%) RES excluding hydro power contribution to electricity generation (%) Coal contribution to electricity generation (%) Oil contribution to electricity generation (%) Natural gas contribution to	Ambient particulate matter

				Low-carbon lifestyle publicity		electricity generation (%) Coverage rate of electricity imports by exports Highest value of the power absorbed or supplied, in an hour during the year (MW) Electricity consumption intensity in the economy (elec. Cons./GDP) Coverage rate of fossil fuels imports by exports Carbon dioxide emissions intensity in the economy (CO_2/GDP) Total energy real index for industry and households Accumulated number of policy-driven instruments Accumulated number of market-driven instruments	

Appendix B: Survey template for data computation

Context

The questions are designed for a remote, off-grid northern community. For example, Old Crow, the northernmost community in Yukon, Canada, is not accessible by road. With a population of approximately 240 indigenous residents, most goods, including diesel, are flown by an airplane into the community to support essential services, as noted in a report by Schonewille & Anderton (2005). In a community like Old Crow, household heating is typically achieved through space and water heating systems. Space heating is usually provided by locally sourced firewood in wood stoves and oil heaters, with electric baseboards serving as a backup, particularly around water pipes. Water heating is generally powered by electric water heaters, and electricity for household appliances comes from a central diesel-powered generating station. When assessing diesel dependency in this community, to derive the data on emissions estimates, the focus would be on local diesel consumption emissions (including emissions from the central power generator) and transportation-related emissions from importing diesel.

Infrastructure-level questions

Two groups of individuals will be interviewed at this level: facility managers and energy utility managers within the community. The interviews aim to collect data on the current state of diesel consumption and assess how changes in diesel supply impact each infrastructure within the community. The gathered information will be used for estimating local carbon emissions and assessing how variations in fuel quantities affect the operation of essential infrastructure.

- *What is the average volume of diesel transported into the community on a weekly basis?*
- *What is the average fuel required by the airplanes used to import diesel on a weekly basis?*
- *Provide a list of community facilities supported by energy services.*

- *Specify which facilities are connected to the following areas: health, education, household energy services, and social connection.*
- *How much diesel is consumed by local transportation systems within the community?*
- *What is the monthly diesel requirement for the ideal operation of each facility within the community?*
- *On average, how many hours per day do energy services support these facilities?*
- *What quantity of diesel is needed to power the central electricity generating system and other central heating systems in the community?*
- *In a scenario where the community faces a reduction of [insert fuel change quantity] in available diesel due to unforeseen events, with no immediate alternatives to meet demand, how long could each infrastructure operate? Please provide an estimated change in operational hours for each facility, considering reduced availability of energy services such as space heating, water heating, lighting, etc.*

Expert-level data collection

At this level, we aim to gather data on how changes in infrastructure operation affect each well-being driver. Experts may include community administrators or individuals with deep knowledge of the community's structure and operations across key services. These experts will be provided with data from the infrastructure survey and are expected to provided quantitative assessments of the potential impacts of fuel change on various aspects of community life. The questions below focus on four key areas: social connections, health services, education, and household living conditions.

Please review the infrastructure data provided and use your knowledge of the community to estimate potential changes in each area of community well-being by responding to the following questions:

- *Social connections: What is the average number of community social, cultural, and religious activities held weekly? Given the changes in fuel availability affecting the operational capacity of physical spaces used to enable community cohesion, what is the expected change in the number of these events?*
- *Health services: What is the typical number of weekly medical procedures at community health centers? Due to changes in fuel availability impacting the optimal operation of health facilities, what is the projected change in the number of procedures and consultations that could occur?*
- *Education: What are the ideal instructional hours available to community learners per day? With changes in the operational capacity of schools and daycares, how many hours of instructional time will be available to learners in the community?*
- *Household living conditions: What is the average number of hours per day that households currently access energy services? Given the reduced operation of central power generators and heating systems, what is the expected change in daily access to energy services?*

Household-level survey

In this section, we assume that one household representative will be the respondent for this survey per household. The following questions are required at this level:

- *How many people live in this household?*
- *Is your household connected to the community's central power and heating systems?*
- *What essential services do you require to achieve daily fulfillment as a household? (Examples might include access to reliable healthcare services, schools, etc.)*

- *On a scale of 1 to 10, where 1 means extremely dissatisfied and 10 means extremely satisfied, how satisfied are you with your life these days?*
- *Due to a fuel shortage, the community's available fuel supply has been reduced by 10%, impacting critical services. Given the following change, please rate your level of satisfaction in your ability to achieve daily fulfillment in light of these changes (on a scale of 1 to 10, where 1 means extremely dissatisfied and 10 means extremely satisfied):*
    - ***Social and Cultural Participation:*** *Your household's participation in community social and cultural events is likely to decrease to [insert data from expert analysis]. How satisfied are you now with your household's ability to achieve daily fulfillment?*
    - ***Healthcare Services:*** *The community health centre is expected to reduce its operating hours by [insert data from expert analysis]. How satisfied are you now with your ability to achieve daily fulfillment?*
    - ***Education:*** *Due to the fuel shortage, schools will not operate for the ideal number of hours, and instructional hours available to households will be [insert data from expert analysis]. How satisfied are you now with your household's ability to achieve daily fulfillment?*
    - ***Energy and Heating Services:*** *The community's central power and heating systems will only be available for [insert data from expert analysis]. How satisfied are you now with your ability to achieve daily fulfillment?*

Table B.1:Mock survey responses from infrastructure-level data-gathering process

Data collection questions	V1 - Social & cultural centers	V2 - Community health centers	V3 - Schools & daycares	V4 - Community central power generator	V5 - Community central heating
What is the average weekly fuel quantity required to sustain the ideal operation for each infrastructure	200 litres to support social, cultural and religious centres	1000 litres to support emergency and routine care	100 litres per week to support learning activities	2000 litres weekly to support household energy services	500 litres to support household heating needs
In a scenario where the community experiences a 10% reduction in available fuel for consumption, with no immediate alternatives, how long could each infrastructure operate?	Social, cultural, and religious spaces would operate for an average of 8 hours per week, down from 10 hours per week.	Health centers can open for 14 hours per day, compared to the ideal of 16 hours per day.	Schools and daycares can open for 6 hours per day, compared to the ideal of 8 hours per day.	Electricity is available for 21 hours per day across households, compared to the ideal of 24/7 availability from the community's central power generator.	Heating systems are limited to an average of 2 hours per day across households, down from 3 hours per day before the fuel reduction.

Table B.2: Mock survey responses from baseline evaluation of well-being at the household level

Purpose	Household-level survey	Survey response for household A	Survey response for household B
Identify key well-being drivers per household	Please rank the following in the order of importance to your household. Additionally, please specify any other factors not listed that significantly contribute to your family's daily fulfillment.	Social connection Health Education access Household living conditions	
Baseline well-being assessment survey before the fuel change scenario. This is a standard measure of well-being question	All things considered, how satisfied are you with your life as a whole these days? Please give a score from 1 to 10, where 1 means extremely dissatisfied, and 10 means extremely satisfied	8	6

from the National Economics Foundation.			

Table B.3: Mock data table showing expert assessment of change in well-being driver and mock survey responses from households. The table also shows the computed WSFC derived from expert opinion and HWWD derived from household responses.

Key well-being driver	Expert assessment of change based on infrastructure-level data	WSFC (expressed in some unit of well-being)	Household-level question (required to evaluate HWWD)	Survey response for household A ($P_n = 3$)	Survey response for household B ($P_n = 5$)	HWWD for household A (expressed in some unit of well-being)	HWWD for household B (expressed in some unit of well-being)
Social connection	Due to changes in the operational capacity of community physical spaces, the number of social, cultural, and religious activities will be decreased by 30%.	0.3	Given this limitation in your ability to participate in social networks, how satisfied are you now with your ability to achieve daily fulfilment? Please give a score from 1 to 10, where 1 means extremely dissatisfied, and 10 means extremely satisfied.	7	4	0.125	0.33
Health	Due to the reduced operations of community health centres, the number of medical consultations	0.15	Given this change in access to healthcare services, how satisfied are you now with your ability to achieve daily	4	3	0.5	0.5

	and procedures would be reduced by 15%.		fulfilment? Please give a score from 1 to 10, where 1 means extremely dissatisfied, and 10 means extremely satisfied				
Education	Due to the reduced operations of schools and daycares, instructional hours available to household members would be reduced by 15%.	0.15	Given this change in the instructional hours available to members of your household, how satisfied are you now with your ability to achieve daily fulfilment? Please give a score from 1 to 10, where 1 means extremely dissatisfied and 10 means extremely satisfied.	6	5	0.25	0.167
Household living conditions	Due to the reduced operations of the central community power generator and heating systems, households would experience a 10% decrease in the number of hours that energy	0.1	Given this change in the number of hours that your household can operate energy services, how satisfied are you now with your ability to achieve daily fulfilment? Please give a score from 1 to 10, where 1 means extremely	3	3	0.625	0.5

	services could be available		dissatisfied and 10 means extremely satisfied.				

Bibliography

Acevedo, R. A., & Lorca-Susino, M. (2021). The European Union oil dependency: a threat to economic growth and diplomatic freedom. International Journal of Energy Sector Management, 15(5), 987–1006. https://doi.org/10.1108/IJESM-10-2020-0010

Ahmad, Q. K., Anisimov, O., Arnell, N., Brown, S., Burton, I., Campos, M., Canziani, O., Carter, T., Cohen, S. J., Desanker, P., Easterling, W., Fitzharris, B. B., Forbes, D., Gitay, H., Githeko, A., Gonzalez, P., Gubler, D., Gupta, S., Haines, A., … Wilbanks, T. (2001). Climate change 2001: impacts, adaptation, and vulnerability: A report of working group ii of the intergovernmental panel on climate change. https://www.ipcc.ch/2001/02/19/climate-change-2001-impacts-adaptation-and-vulnerability/

Benedictow, A., Fjærtoft, D., & Løfsnæs, O. (2013). Oil dependency of the Russian economy: An econometric analysis. Economic Modelling, 32(1), 400–428. https://doi.org/10.1016/j.econmod.2013.02.016

Bhattacharyya, S. C. (2009). Fossil-fuel dependence and vulnerability of electricity generation: Case of selected European countries. Energy Policy, 37(6), 2411–2420. https://doi.org/10.1016/J.ENPOL.2009.02.031

Biddle, S. J. H., & Ekkekakis, P. (2005). Physically active lifestyles and well-being. The Science of Well-Being. https://doi.org/10.1093/ACPROF:OSO/9780198567523.003.0006

Bridge, G., Bouzarovski, S., Bradshaw, M., & Eyre, N. (2013). Geographies of energy transition: Space, place and the low-carbon economy. Energy Policy, 53, 331–340. https://doi.org/10.1016/J.ENPOL.2012.10.066

Busch, T., Weinhofer, G., & Hoffmann, V. H. (2011). The carbon performance of the 100 largest US electricity producers. Utilities Policy, 19(2), 95–103. https://doi.org/10.1016/j.jup.2010.12.002

Chalvatzis, K. J., & Ioannidis, A. (2017). Energy supply security in the EU: Benchmarking diversity and dependence of primary energy. Applied Energy, 207, 465–476. https://doi.org/10.1016/j.apenergy.2017.07.010

Chang, H. I. (2013). Stochastic Kaya model and its applications. Munich Personal RePEc Archive. https://mpra.ub.uni-muenchen.de/55099/

Chapra, S. C., & Canale, R. P. (2015). Numerical methods for engineers Seventh Edition. McGraw-Hill Education.

Chen, M., Yang, L., Hu, M., & Montero, D. (2020). Towards green and low-carbon development in chinese cities. Urbanisation, 7(1_suppl), S42-S60. https://doi.org/10.1177/2455747120918702

Chen, P.-Y., Chen, S.-T., Hsu, C.-S., & Chen, C.-C. (2016). Modelling the global relationships among economic growth, energy consumption and CO_2 emissions. Renewable and Sustainable Energy Reviews, 65, 420–431. https://doi.org/10.1016/j.rser.2016.06.074

Clarkson, R., & Deyes, K. (2002). Report: *Estimating the Social Cost of Carbon Emissions*. Department of Environment Food and Rural Affairs. https://www.civil.uwaterloo.ca/maknight/courses/CIVE240-05/week3/carbon%20social%20cost.pdf

Cohen, J. P. (2014). Production functions for medical services. Encyclopedia of Health Economics, 180–183. https://doi.org/10.1016/B978-0-12-375678-7.01010-5

DFID. (1999). Sustainable livelihoods guidance sheets. Report by The Department for International Development (DFID). https://www.livelihoodscentre.org/documents/114097690/114438878/Sustainable+livelihoods+guidance+sheets.pdf/594e5ea6-99a9-2a4e-f288-cbb4ae4bea8b?t=1569512091877

Diener, E., & Biswas-Diener, R. (2002). Will money increase subjective well-being? A literature review and guide to needed research. Social Indicators Research, 57(2), 119–169. https://doi.org/10.1023/A:1014411319119

Dolan, P., Peasgood, T., & White, M. (2008). Do we really know what makes us happy? A review of the economic literature on the factors associated with subjective well-being. Journal of Economic Psychology, 29(1), 94–122. https://doi.org/10.1016/J.JOEP.2007.09.001

Dovjak, M., & Kukec, A. (2019). Health outcomes related to built environments. creating healthy and sustainable buildings, 43–82. https://doi.org/10.1007/978-3-030-19412-3_2

Environment and Climate Change Canada. (n.d.). Emission factors and reference values. Retrieved June 5, 2024, from https://www.canada.ca/en/environment-climate-change/services/climate-change/pricing-pollution-how-it-will-work/output-based-pricing-system/federal-greenhouse-gas-offset-system/emission-factors-reference-values.html

Evans, G., & Phelan, L. (2016). Transition to a post-carbon society: Linking environmental justice and just transition discourses. Energy Policy, 99, 329–339. https://doi.org/10.1016/j.enpol.2016.05.003

Evans, G. R. (2008). Transformation from “Carbon Valley” to a “Post-Carbon Society” in a climate change hot spot: the coalfields of the Hunter Valley, New South Wales, Australia. Ecology and Society 13(1): 39. http://www.ecologyandsociety.org/vol13/iss1/art39/

Fang, Y. (2011). Economic welfare impacts from renewable energy consumption: The China experience. Renewable and Sustainable Energy Reviews, 15(9), 5120–5128. https://doi.org/10.1016/j.rser.2011.07.044

Fernandes, V. A., Rothfuss, R., Hochschild, V., Da Silva, M. A. V., Da Silva, W. R., Steiniger, S., & Dos Santos, T. F. (2019). Urban resilience in the face of fossil fuel dependency: the case of Rio de Janeiro’s urban mobility. Urbe. Revista Brasileira de Gestão Urbana, 11. https://doi.org/10.1590/2175-3369.011.E20180160

Fine, M., & Glendinning, C. (2005). Dependence, independence or inter-dependence? Revisiting the concepts of “care” and “dependency.” Ageing and Society, 25(4), 601–621. https://doi.org/10.1017/S0144686X05003600

Flouri, E. (2004). Subjective Well-Being in Midlife: The role of involvement of and closeness to parents in childhood. Journal of Happiness Studies, 5(4), 335–358. https://doi.org/10.1023/B:JOHS.0000048461.21694.92

Fraser, N., & Gordon, L. (1994). A Genealogy of Dependency: Tracing a keyword of the U.S. welfare state. Signs, 19(2), 309–336. http://www.jstor.org/stable/3174801

Frijters, P., Haisken-DeNew, J. P., & Shields, M. A. (2004). Money does matter! evidence from increasing real income and life satisfaction in East Germany following reunification. American Economic Review, 94(3), 730–740. https://doi.org/10.1257/0002828041464551

Gaertner, W. (1993). Amartya Sen: Capability and well-being. The quality of life, 62–66. https://doi.org/10.1093/0198287976.003.0005

Greene, D. L. (2010). Measuring energy security: Can the United States achieve oil independence? Energy Policy, 38(4), 1614–1621. https://doi.org/10.1016/j.enpol.2009.01.041

Greco, S., Ishizaka, A., Tasiou, M., & Torrisi, G. (2019). On the Methodological Framework of Composite Indices: A Review of the Issues of Weighting, Aggregation, and Robustness. Social Indicators Research, 141(1), 61–94. https://doi.org/10.1007/S11205-017-1832-9/FIGURES/1

Greer, M. (2012). Electricity marginal cost pricing: Applications in eliciting demand responses. 1–346. https://doi.org/10.1016/C2010-0-65920-7

Guite, H. F., Clark, C., & Ackrill, G. (2006). The impact of the physical and urban environment on mental well-being. Public Health, 120(12), 1117–1126. https://doi.org/10.1016/J.PUHE.2006.10.005

Gupta, R., Sheng, X., van Eyden, R., & Wohar, M. E. (2021). The impact of disaggregated oil shocks on state-level real housing returns of the United States: The role of oil dependence. Finance Research Letters, 43, 102029. https://doi.org/10.1016/j.frl.2021.102029

Halser, C., & Paraschiv, F. (2022). Pathways to overcoming natural gas dependency on Russia; the German case. Energies 2022, Vol. 15, Page 4939, 15(14), 4939. https://doi.org/10.3390/EN15144939

Huang, J., & Słomczyński, K. M. (2003). The dimensionality and measurement of economic dependency: A research note. International Journal of Sociology, 33(4), 82–98. https://www.jstor.org/stable/20628696

Hao, F., Liu, X., & Michaels, J. L. (2020). Social capital, carbon dependency, and public response to climate change in 22 European countries. Environmental Science & Policy, 114, 64–72. https://doi.org/10.1016/j.envsci.2020.07.028

Hartog, J., & Oosterbeek, H. (1998). Health, wealth and happiness: why pursue a higher education? Economics of Education Review, 17(3), 245–256. https://doi.org/10.1016/S0272-7757(97)00064-2

Headey, B., & Wooden, M. (2004). The Effects of Wealth and Income on Subjective Well-Being and Ill-Being. Economic Record, 80(SPEC. ISS.), S24–S33. https://doi.org/10.1111/J.1475-4932.2004.00181.X

Helliwell, J. F. (2003). How's life? Combining individual and national variables to explain subjective well-being. Economic Modelling, 20(2), 331–360. https://doi.org/10.1016/S0264-9993(02)00057-3

Henderson, K. E., & Sommer, J. (2022). Aiding fossil fuel dependency: a cross-national analysis of energy sector aid, national autonomy, and CO_2 emissions in 122 nations. International Journal of Sociology, 52(1), 25–48. https://doi.org/10.1080/00207659.2021.2009273

Hill, M., & Engle, N. L. (2013). Adaptive Capacity: Tensions across Scales. Environmental Policy and Governance, 23(3), 177–192. https://doi.org/10.1002/EET.1610

Hoffmann, V. H., & Busch, T. (2008). Corporate Carbon Performance Indicators. Journal of Industrial Ecology, 12(4), 505–520. https://doi.org/10.1111/J.1530-9290.2008.00066.X

Hou, X., Zhou, J., Zhang, L., & Yang, Q. (2021). Construction and measurement of China's comprehensive energy dependence index. Energy Reports, 7, 4516–4529. https://doi.org/10.1016/J.EGYR.2021.07.030

International Atomic Energy Agency (IAEA). (2005). Energy Indicators for Sustainable Development: Guidelines and Methodologies, Non-serial Publications, Vienna. https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1222_web.pdf

Ide, T. (2020). Recession and fossil fuel dependence undermine climate policy commitments. Environmental Research Communications, 2(10). https://doi.org/10.1088/2515-7620/ABBB27

IEA. (2017). WEO-2017 Special Report: Energy Access Outlook – Analysis - International Energy Agency (IEA). https://www.iea.org/reports/energy-access-outlook-2017

IEA. (2021). Report: Net Zero by 2050 – Analysis - International Energy Agency(IEA). https://www.iea.org/reports/net-zero-by-2050

Indigenous Clean Energy (ICE). (2022). Waves of Change: Indigenous clean energy leadership for Canada's clean, electric future. https://climateinstitute.ca/wp-content/uploads/2022/02/ICE-report-ENGLISH-FINAL.pdf

International Energy Agency (IEA). (2022). Report: Canada 2022 - Energy Policy Review. https://www.iea.org/reports/canada-2022

IPCC. (2023). Summary for Policymakers. In: Climate Change 2023: Synthesis Report. A Report of the Intergovernmental Panel on Climate Change (IPCC). https://www.ipcc.ch/report/sixth-assessment-report-cycle/

IPCC WG2. (n.d.). Adaptive capacity - AR4 WGII Chapter 6: Coastal Systems and Low-Lying Areas. Retrieved July 1, 2023, from https://archive.ipcc.ch/publications_and_data/ar4/wg2/en/ch6s6-6-4.html

Jacal, S., Straubinger, F. B., Benjamin, E. O., & Buchenrieder, G. (2022). Economic costs and environmental impacts of fossil fuel dependency in sub-Saharan Africa: A Nigerian dilemma. Energy for Sustainable Development, 70, 45–53. https://doi.org/10.1016/J.ESD.2022.07.007

Jain, V. (2019). Fossil Fuels, GHG Emissions and Clean Energy Development: Asian Giants in a Comparative Perspective. Millennial Asia, 10(1), 1–24. https://journals.sagepub.com/doi/full/10.1177/0976399619825687

Kaiser, M. J., & McAllister, E. W. (2023). Specifications. Pipeline Rules of Thumb Handbook, 1089–1146. https://doi.org/10.1016/B978-0-12-822788-6.00019-0

Kakwani, N., & Son, H. H. (2016). Social Welfare Functions and Development. Palgrave Macmillan UK. https://doi.org/10.1057/978-1-137-58325-3

Knight, K. W. (2019). Does Fossil Fuel Dependence Influence Public Awareness and Perception of Climate Change? A Cross-National Investigation. International Journal of Sociology. Https://Doi.Org/10.1080/00207659.2018.1515702 , 48(4), 295–313

Kofinas, G. P., & Chapin, F. S. (2009). Sustaining Livelihoods and human well-being during social-ecological change. Principles of Ecosystem Stewardship: Resilience-Based Natural Resource Management in a Changing World, 55–75. https://doi.org/10.1007/978-0-387-73033-2

Kolker, A., Garber-Slaght, R., Anderson, B., Reber, T., Zyatitsky, K., & Pauling, H. (2022). Report: Geothermal Energy and Resilience in Arctic Countries. https://www.nrel.gov/docs/fy22osti/80928.pdf

Kuik, O. (2003). Climate Change Policies, Energy Security and Carbon Dependency Trade-offs for the European Union in the Longer Term. International Environmental Agreements: Politics, Law and Economics: 221–242, 3, 221–242. https://doi.org/10.1023/B:INEA.0000005625.44125.54

Kudryavtsev, L. D. (2020). Function. In Encyclopedia of Mathematics. https://encyclopediaofmath.org/wiki/Function

Lafortune, G., Fuller, G., Schmidt-Traub, G., & Kroll, C. (2020). How Is Progress towards the Sustainable Development Goals Measured? Comparing Four Approaches for the EU. Sustainability 2020, Vol. 12, Page 7675, 12(18), 7675. https://doi.org/10.3390/SU12187675

Lane, T. E., & Vanderschuren, M. J. W. A. (2009). Potential transport energy demand and oil dependency mitigation measures. WIT Transactions on Ecology and the Environment, 121, 225–236. https://doi.org/10.2495/ESU090201

Lee, S. J., & Kim, Y. (2015). Searching for the meaning of community well-being. In R. Phillips & C. Wong (Eds.), Community Well-Being and Community Development: Conceptions and Applications (pp. 21–36). https://doi.org/10.1007/978-3-319-12421-6_2

Li, Q., & Chen, H. (2021). The relationship between human well-being and carbon emissions. In Sustainability (Switzerland) (Vol. 13, Issue 2, pp. 1–12). MDPI AG. https://doi.org/10.3390/su13020547

Ligus, M., & Peternek, P. (2021). The sustainable energy development index—an application for European union member states. Energies, 14(4). https://doi.org/10.3390/en14041117

Liu, L., & Wu, J. (2021). Ecosystem services-human well-being relationships vary with spatial scales and indicators: The case of China. Resources, Conservation and Recycling, 172, 105662. https://doi.org/10.1016/j.resconrec.2021.105662

Liu, S., Yang, Y., & Forrest, J. Y.-L. (2022). Grey Relational Analysis Models. 77–124. https://doi.org/10.1007/978-981-19-6160-1_5

Lovekin, D., & Heerema, D. (2019). The True Cost of Energy in Remote Communities: Understanding diesel electricity generation terms and economics (2nd ed.). Pembina Institute. https://www.pembina.org/reports/diesel-cost-backgrounder-2019.pdf

Look, W., Haggerty, M., & Mazzone D. (2022). Community Hubs to Support Energy Transition. Report by Resources for the Future (RFF). https://media.rff.org/documents/Community_Hubs_-_IB_22-02.pdf

Loomis, L., & Sternberg, S. (1990). Advanced Calculus (Revised ed.). Jones and Bartlett Publishers International.

Marques, A. C., Fuinhas, J. A., & Pereira, D. A. (2018). Have fossil fuels been substituted by renewables? An empirical assessment for 10 European countries. Energy Policy, 116, 257–265. https://doi.org/10.1016/j.enpol.2018.02.021

Meier, S., & Stutzer, A. (2008). Is Volunteering Rewarding in Itself? Economica, 75(297), 39–59. https://doi.org/10.1111/J.1468-0335.2007.00597.X

Mercer, N., Parker, P., Hudson, A., & Martin, D. (2020). Off-grid energy sustainability in Nunatukavut, Labrador: Centering Inuit voices on heat insecurity in diesel-powered communities. Energy Research & Social Science, 62, 101382. https://doi.org/10.1016/J.ERSS.2019.101382

Mertins-Kirkwood, H. (2018). Making decarbonization work for workers: Policies for a just transition to a zero-carbon economy in Canada. Report by the Canadian Centre for Policy Alternatives.https://policyalternatives.ca/sites/default/files/uploads/publications/National%20Office/2018/01/Making%20Decarbonization%20Work.pdf

Michaelson, J., Mahony, S., & Schifferes, J. (2012). Measuring Well-being: A guide for practitioners. Report by the New Economics Foundation. https://neweconomics.org/2012/07/measuring-well-being

Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2009). Preferred Reporting Items For Systematic Reviews And Meta-Analyses: the PRISMA statement. BMJ, 339(7716), 332–336. https://doi.org/10.1136/BMJ.B2535

Natural Resources Canada. (2011). Status of remote/off grid communities in Canada. A Report by Aboriginal Affairs and Northern Development Canada (AANDC) and Natural Resources Canada (NRCan). https://natural-resources.canada.ca/sites/nrcan/files/canmetenergy/files/pubs/2013-118_en.pdf

Nelson, D. R., Adger, W. N., & Brown, K. (2007). Adaptation to environmental change: contributions of a resilience framework. Annual Review of Environment and Resources, 32, 395–419. https://doi.org/10.1146/ANNUREV.ENERGY.32.051807.090348

Newns, W. F. (1967). Functional Dependence. The American Mathematical Monthly, 74(8), 911. https://doi.org/10.2307/2315264

Nykamp DQ. (n.d.). Partial derivative by limit definition - Math Insight. Retrieved May 5, 2024, from https://mathinsight.org/partial_derivative_limit_definition

Orii, L., Alonso, L., & Larson, K. (2020). Methodology for Establishing Well-Being Urban Indicators at the District Level to be Used on the City Scope Platform. Sustainability 2020, Vol. 12, Page 9458, 12(22), 9458. https://doi.org/10.3390/SU12229458

O'Sullivan, E., & McHardy, M. (2008). The Community Well-being Index (CWB): Well-being in First Nations Communities, Present, Past, and Future. Report by the Aboriginal Policy Research Consortium International (APRCi). http://thompsonbooks.com/wp-content/uploads/2020/02/AbWB_Ch6.pdf

Pearce, T., Smit, B., Duerden, F., Ford, J. D., Goose, A., & Kataoyak, F. (2010). Inuit vulnerability and adaptive capacity to climate change in Ulukhaktok, Northwest Territories, Canada. Polar Record, 46(2), 157–177. https://doi.org/10.1017/S0032247409008602

Pearce, D. (2002). Report: *The Social Cost of Carbon and its Policy Implications*. Environmental Policy Seminar, Oxford University. https://www.ucl.ac.uk/~uctpa15/SOCIAL_COST_OF_CARBON.pdf

Pembina Institute. (2021a). Diesel Subsidies For Remote Communities-Simplified. https://wwf.ca/wp-content/uploads/2021/10/Diesel-Subsidies-for-Remote-Communities_v2.pdf

Pembina Institute. (2021b). Diesel Reduction Progress in Remote Communities. Renewables in Remote Communities Conference 2021. https://www.pembina.org/pub/diesel-reduction-progress-remote-communities

Phillips, M., & Dickie, J. (2015). Climate change, carbon dependency and narratives of transition and stasis in four English rural communities. Geoforum, 67, 93–109. https://doi.org/10.1016/j.geoforum.2015.10.011

Pichler, F. (2006). Subjective quality of life of young Europeans. Feeling happy but who knows why. Social Indicators Research, 75(3), 419–444. https://doi.org/10.1007/s11205-004-4337-2

Portugal-Pereira, J., & Esteban, M. (2014). Implications of paradigm shift in Japan's electricity security of supply: A multi-dimensional indicator assessment. Applied Energy, 123, 424–434. https://doi.org/10.1016/j.apenergy.2014.01.024

Raimi, D., Carley, S. & Konisky, D. (2021). Mapping county-level vulnerability to the energy transition in US fossil fuel communities. Sci Rep 12, 15748 https://doi.org/10.1038/s41598-022-19927-6

Redish, E. F. (2021). Using Math in Physics: 1. Dimensional Analysis. The Physics Teacher, 59(6), 397–400. https://doi.org/10.1119/5.0021244

Redlich, O. (1969). Intensive And Extensive Properties. Lawrence Berkeley National Laboratory Publications. https://escholarship.org/uc/item/5mp6r34r

Ren, J., & Dong, L. (2018). Evaluation of electricity supply sustainability and security: Multi-criteria decision analysis approach. Journal of Cleaner Production, 172, 438–453. https://doi.org/10.1016/j.jclepro.2017.10.167

Riedel, R. (2021). Green conservatism or environmental Nativism?: Exploring carbon dependency as populist political strategy in Poland. Zeitschrift Fur Vergleichende Politikwissenschaft, 15(2), 207–227. https://doi.org/10.1007/S12286-021-00490-9

Rigoberto, J., & Daza, P. (2004). The utility function and the emotional well-being function. EJBO - Electronic Journal of Business Ethics and Organization Studies, 9(2), 22. https://jyx.jyu.fi/handle/123456789/25363

Schmidt, G. (2008). Professional Work in Remote Northern Communities: A Social Work Perspective. The Community Development Institute at the University of Northern British Columbia. https://www.unbc.ca/sites/default/files/sections/community-development-institute/g_schmidt_cdi_paper.pdf

Schonewille, B., & Anderton, I. (2005). Report: *Vuntut Gwitchin First Nation Community Energy Baseline Study*. https://emrlibrary.gov.yk.ca/energy/vgfn_community_energy_baseline.pdf

Smit, B., & Wandel, J. (2006). Adaptation, Adaptive Capacity and Vulnerability. Global Environmental Change, 16(3), 282–292. https://doi.org/10.1016/J.GLOENVCHA.2006.03.008

Solingen, E. (1991). Managing Energy Vulnerability: Brazil's Adjustment to Oil Dependency. SSRN Electronic Journal. https://doi.org/10.2139/SSRN.3274883

Sovacool, B. K., & Griffiths, S. (2020). The cultural barriers to a low-carbon future: A review of six mobility and energy transitions across 28 countries. Renewable and Sustainable Energy Reviews, 119, 109569. https://doi.org/10.1016/j.rser.2019.109569

Stiglitz, J., Sen, A., & Fitoussi, J. (2009). Report by the Commission on the Measurement of Economic Performance and Social Progress. https://ec.europa.eu/eurostat/documents/8131721/8131772/Stiglitz-Sen-Fitoussi-Commission-report.pdf

Stoll, L., Michaelson, J., & Seaford, C., (2012). Well-being evidence for policy: A review. A Report by the New Economics Foundation https://neweconomics.org/uploads/files/10b8aabd90c5771ff9_a0m6bvv5a.pdf

Talmage, C. A. (2020). Community Development, Quality of Life, and Community Well-Being: Three Fields Ripe with Opportunities for Future Research and Practice. Community Development Practice, 24. https://egrove.olemiss.edu/cdpractice/vol24/iss1/4/

Thombs, R. P. (2022). The asymmetric effects of fossil fuel dependency on the carbon intensity of well-being: A U.S. state-level analysis, 1999–2017. Global Environmental Change, 77, 102605. https://doi.org/10.1016/J.GLOENVCHA.2022.102605

United Nations Environment Programme (UNEP) (2009). Rethinking the economic recovery: a global green new deal. https://wedocs.unep.org/xmlui/handle/20.500.11822/7727

Vergara, G. (2018). How Coal Kept My Valley Green: Forest Conservation, State Intervention, and the Transition to Fossil Fuels in Mexico. Environmental History 23, 23(1), 82–105. https://doi.org/10.1093/ENVHIS/EMX126

Vieira, L. C., Longo, M., & Mura, M. (2022). From carbon dependence to renewables: The European oil majors' strategies to face climate change. Business Strategy and the Environment. https://doi.org/10.1002/bse.3185

Vodden, K. and Cunsolo, A. (2021): Rural and Remote Communities; Chapter 3 in Canada in a Changing Climate: National Issues Report, (ed.) F.J. Warren and N. Lulham; Government of Canada, Ottawa, Ontario.

Wang, Q., & Su, M. (2019). Drivers of decoupling economic growth from carbon emission-an empirical analysis of 192 countries using decoupling model and decomposition method. Environmental Impact Assessment Review. https://doi.org/10.1016/j.eiar.2019.106356

Weisser, D. (2004). On the economics of electricity consumption in small island developing states: a role for renewable energy technologies? Energy Policy, 32(1), 127–140. https://doi.org/10.1016/S0301-4215(03)00047-8

Wei-Yu, W., & Nian, Y. (2013). Low Carbon Economy Evaluation Index System and Development Evaluation of Hebei. 2013 Sixth International Conference on Business Intelligence and Financial Engineering, 572–575. https://doi.org/10.1109/BIFE.2013.119

Wheeler, J. A., Gorey, K. M., & Greenblatt, B. (1998). The Beneficial Effects of Volunteering for Older Volunteers and the People They Serve: A Meta-Analysis. The International Journal of Aging and Human Development. https://doi.org/10.2190/VUMP-XCMF-FQYU-V0JH

Wiseman, J., & Brasher, K. (2008). Community well-being in an unwell world: Trends, challenges, and possibilities. Journal of Public Health Policy, 29(3), 353–366. https://www.jstor.org/stable/40207196

Wolfers, J. (2003). Is Business Cycle Volatility Costly? Evidence from Surveys of Subjective Well-Being. International Finance, 6(1), 1–26. https://doi.org/10.1111/1468-2362.00112

World Bank (2013). World Development Report 2013. https://doi.org/10.1596/978-0-8213-9575-2

Xue, L., Haseeb, M., Mahmood, H., Alkhateeb, T. T. Y., & Murshed, M. (2021). Renewable Energy Use and Ecological Footprints Mitigation: Evidence from Selected South Asian Economies. Sustainability 2021, Vol. 13, Page 1613, 13(4), 1613. https://doi.org/10.3390/SU13041613

Touchette, Y., Gass, P & Echeverría, D. (2017).Tracking Diesel Fuel Subsidies In Nunavut Canada The Increasing Cost Of Fossil Fuel Subsidies In Nunavut. A Report by the International

Institute for Sustainable Development(IISD). https://wwf.ca/wp-content/uploads/2020/03/Tracking-Diesel-Fuel-Subsidies_April-2017.pdf

Zhang, J., Huang, G., Liu, L., Zhai, M., Xie, Y., Xin, X., & Meng, H. (2021). Economic sensitivity analysis of dual perspectives induced by energy scarcity for energy-dependent region. Science of The Total Environment, 768, 144876. https://doi.org/10.1016/J.SCITOTENV.2020.144876

Zhang, L. P., & Zhou, P. (2018). A non-compensatory composite indicator approach to assessing low-carbon performance. European Journal of Operational Research, 270(1), 352–361. https://doi.org/10.1016/j.ejor.2018.02.058