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Is energy the golden thread? A systematic review of the impacts of modern and traditional energy use in low- and middle-income countries

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ABSTRACT

Energy has been called the "golden thread" that connects economic growth, social equity and environmental sustainability, but important knowledge gaps exist on the impacts of low- and middle-income country energy interventions and transitions. This study offers perhaps the broadest characterization to date of the patterns and consistency in quantitative and peer-reviewed social science literature considering such impacts. Starting from approximately 80,000 papers identified using a search procedure organized along energy services, technology, and impact dimensions, and structured to achieve breadth and replicability, articles were first screened to yield a relevant subset of 3,000 quantitative papers. Relevance is defined as providing one or more types of impacts on intra-household, household, firm, public service, national economy, or environmental outcomes. A set of heat maps highlights areas of concentration in the literature, namely work that emphasizes the negative health and

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pollution effects of traditional cooking and fossil fuel use. The extent and consistency of evidence for different types of impacts (in terms of direction and statistical significance) is also discussed, which reveals considerable heterogeneity and highlights important knowledge gaps that remain despite rapidly expanding energy scholarship. The patterns of evidence are also surprisingly consistent across methods. The article concludes by articulating several research challenges that should motivate current and future generations of energy and development scholars.

Abbreviations

BRIC	Brazil, Russia, India, China
CBA	Cost-Benefit Analysis
EAP	East Asia and the Pacific
ECA	Europe and Central Asia
GDP	Gross Domestic Product
HHI	Herfindahl-Hirschman Index
IE	Impact Evaluation
LAC	Latin America and the Caribbean
LIC	Low income country
LMIC	Low- and Middle-Income Country
LoMIC	Lower Middle-Income Country
LPG	Liquefied Petroleum Gas
MENA	Middle East and North Africa
OECD	Organisation for Economic Co-operation and Development
SA	South Asia
SDG	Sustainable Development Goal
SETI	Sustainable Energy Transitions Initiative
SSA	Sub-Saharan Africa
UMIC	Upper Middle-Income Country

1. Introduction

Energy has been called the "golden thread" that connects economic growth, social equity and environmental sustainability [1]. Yet today billions live in energy poverty: 15% of the globe lives without electricity [2], many more have only intermittent supplies and low consumption levels [3,4], and 40% depends on solid fuels and polluting technologies for lighting, cooking and heating [5]. In other words, many billions of households, businesses, and other economic agents have not made, or only partially made, a transition to clean and sustainable energy sources [6]. This in turn has massive implications for human livelihoods, development and opportunity, local environmental quality and ecosystem health, and the stability of the future climate.

The establishment of "energy access" targets in the Sustainable Development Goals (SDGs) is partly a response to this stark reality and to the myriad threats to global prosperity that it entails, and was meant to galvanize the international community to mobilize resources to ensure universal access to modern energy. Yet scholarly or policy consensus on how that access impacts well-being remains elusive. As such, policymakers remain limited in their ability to build data-driven predictive models of impacts that can inform design of appropriate interventions and policies [7], assess tradeoffs and interdependencies across interventions, and channel limited resources in the right directions. This review aims to contribute to such an understanding by synthesizing evidence on the impacts of energy, broadly construed, in low- and middle-income countries (LMICs). Two key elements of our approach distinguish the review from prior similar efforts. First, given that energy consumers and end-users ultimately seek to satisfy demand or perceived needs for energy services (rather than, say, kilowatt-hours), an energy services lens is applied to better understand and characterize the sustainable energy challenge [8]. Second, the focus is limited to LMICs because these nations hold the vast majority of the world's energy poor—who also suffer the most from the myriad costs and other harms of inadequate energy. This focus is not meant to minimize the affordability challenge that confronts many lower income people living in high-income countries [9], but recognizes that energy access challenges in high-income countries are distinct, and that their proper characterization requires a different type of review.

We have three primary objectives. The first is to offer the first systematic review of a broad, scattered and disconnected literature on the quantified impacts of energy on society—whether those impacts are positive (for example, when household-level use of solar lanterns extends study hours) or negative (for example, when disposal of batteries creates environmental problems). In doing so, the review is organized to connect energy services (such as heating, cooking, and lighting) with specific energy technologies. Applying this "energy services framework" (discussed further below) serves to highlight how specific technologies may induce tradeoffs in the services they enable and in the types of impacts they produce. Second, topics or questions on which empirical or model-based evidence related to these impacts is robust are identified, in contrast to those where it remains sparse and inconsistent. Here the review describes both consistency across studies pertaining to specific impacts, as well as the nature and relative depth of scholarship pertaining to specific energy services, technologies, and impacts. Importantly, because we feel that a broad perspective on the literature is warranted, study findings are not weighted according to their methods nor are specific types of studies discounted. Instead, the review compares general patterns of evidence in quasi-experimental and experimental studies with those in the broader literature. Third, findings of the review are used to propose a future research agenda for social science research on energy that is in line with identified knowledge gaps as well as critical policy needs and priorities.

The review starts from a set of nearly 80,000 academic articles identified using systematic search procedures and terms aimed at ensuring breadth in coverage and replicability. Screening these for relevance yields 8,192 articles that are then coded in additional detail. Of these, 4,314 are quantitative in nature. The most detailed analyses and commentary—restricted to maintain tractability in the scope of the review—is reserved for the approximately 3,000 papers that consider the impacts of access to energy on both development and/or environmental outcomes (as opposed to the drivers or determinants of access to energy). This emphasis is meant to fill what we judge to be the most critical gap left by prior analyses and reviews, which have extensively covered drivers and determinants of energy transition related to both electrification and clean cooking, e.g., Leach [10], Lewis & Pattanayak [11], Puzzolo et al. [12], and Bonan et al. [13]. In this respect, reviews of the impacts literature have adopted a narrow focus, for example discussing rural electrification in Sub-Saharan Africa, or including only studies that apply specific methods [14–16]. The approach here therefore facilitates consideration of the advantages and disadvantages of more restricted reviews.

Overall, the review reveals that there is not always strong evidence for the claim that access to modern energy services improves environmental and development outcomes. For instance, while there is strong support for the idea that traditional household cooking technology is damaging, evidence on the positive effects of improved cooking technologies is more ambiguous. Meanwhile, fossil-fuel based electricity grids induce important tradeoffs between improved productivity and

income, on the one hand, and health and local and global environmental quality, on the other, due to the contribution of combustion of such fuels to air pollution and climate change [17]. Furthermore, in some domains (e.g., health care delivery), and for some technologies (e.g., decentralized renewables), evidence is thin, inconsistent, or even invisible in the literature—meaning that there are very few studies in support of (or against) widely held beliefs about impacts. Among the eight types of energy services we consider (cooking, heating, cooling, lighting, appliances for consumption, agricultural production/income generation, non-agricultural production/income generation, and transportation), there is considerable concentration in the literature on cooking: over half of the reviewed quantitative impacts studies address that end use. There is also asymmetry in the types of impacts studied, with individual or household health and climate effects receiving substantial attention, compared to much less consideration of impacts on gender equity, household education and income, and local environmental quality; or on addressing the agriculture or service sectors and the quality of public services. On the basis of these findings, it thus appears that the energy thread is not always golden: tradeoffs are common between income and other development (e.g., health or environmental quality) outcomes. The review concludes with reflections on a research agenda that would help inform understanding around key knowledge gaps.

2. Background: Prior reviews of the social dimensions of energy transitions and technology

Before describing the methods and results of the review, it is worth highlighting prior related literature—identified through non-systematic searches and the expert knowledge of the full team of researchers involved in the review—that helped motivate it and inform its construction.[1] One important influence is in recent scholarship noting the underrepresentation of social science research in the broader energy literature, and the fact that many energy researchers undervalue social science discoveries and marginalize diverse and interdisciplinary perspectives [18,19]. A misplaced faith in technological solutions threatens efforts to induce a transition to a more sustainable and just energy future because proposals that ignore social phenomena often fail to deliver on intended goals. The problems with technology-centered perspectives stem from a lack of acceptance and demand among users [20,21], underappreciation for energy consumers' preferences [22], a limited understanding of the role of intermediary organizations in facilitating the adoption and diffusion of technologies into common use [23,24], as well as behavioral feedbacks, such as rebound effects, whereby increased consumption offsets savings from use of more efficient technology [25,26]. As such, it is vitally important to assess how solutions perform in the real world, using empirical evaluation methods, and to shed light on the mechanisms underlying that performance, as complex as those may be [27].

It is also worth considering briefly what the "energy transition" concept means. Given the complexity of the processes that underlie energy transitions, and the contexts in which they take place, a consensus definition proves difficult. For instance, Sovacool [28] reviews literature on the temporal dynamics of energy transitions and concludes that they may occur much more rapidly than is commonly thought. Smil [29] highlights ten case studies in which such transitions occurred quickly (in periods of 1–16 years) and affected nearly one billion people in total, three of which consider experiences in LMICs. Rapid transitions away from solid fuels have similarly occurred among the large urban populations in both India and China [30], and likely in many other settings. Grubler et al. [31] also document patterns, processes, and timescales that characterize diffusion in energy technologies, and note that many such technologies diffuse within a couple of decades or less, though other energy transitions have unfolded over centuries. Van Benthem [32] considers a related issue in asking whether LMICs can "leapfrog" high-income countries and obviate the need for their own transition to an energy-efficient and low-carbon economy. He finds little evidence to support this hypothesis due to a shift over time towards more energy-intensive consumption and composition changes affecting industry and arising from outsourcing.[2] For our purposes, this review follows Sovacool [28] and defines an energy transition rather broadly as "a change in an energy system, usually to a particular fuel source, technology, or prime mover (a device that converts energy into useful services)."

There have been prior reviews of the impacts as well as drivers of energy transitions in LMICs (Table 1 presents a summary). Much of this prior attention has been focused on drivers, determinants and barriers, or on the diffusion and adoption of specific energy technology in low-income contexts. In an important early paper in the energy literature, Leach [10] conducted cross-country and cross-sectional regression analysis of data from 40 low-income countries to characterize the factors that are related to household substitution of traditional biomass fuels with modern energy sources. This analysis suggested that urbanization and income were more important determinants of transition than fuel prices, and proposed that this reflected availability and liquidity constraints that limit uptake of modern fuel-using appliances as well as marketed quantities—which are typically sold in large containers—of fuels such as liquefied petroleum gas (LPG). Similar factors are highlighted in Pachauri's [30] country comparison of India and China. Leach further suggested that policies should target a) improved supply of modern fuels via investment in transport and storage infrastructure, increased availability of fuel cylinders and incentives to improve distribution; and b) reduced cost or subsidies for equipment and smaller fuel containers, to address cash availability constraints. Others have noted the importance of government support for suppliers while highlighting that fuel pricing matters in shifting user behavior, e.g., in China for higher-efficiency stoves, and in Indonesia for LPG or Brazil for use of ethanol in vehicles [28]. Indeed, the private sector and even government-supported utilities have often failed to invest in rural markets due to the high cost and risks associated with reaching scattered and low-consuming customers [33,34].

Reviews or critical appraisals of the drivers of energy technology adoption have also considered specific problems, such as the use of improved cookstoves or modern fuels [11,12,49], extension and take-up of electricity connections [13,50], or deployment of renewable energy technologies [36,51]. Though each of these offer somewhat different perspectives, they nonetheless highlight a set of common determinants—low cost of solutions, higher income and education, urbanization and connectedness, efficient and equitable subsidies that benefit the poor, learning from neighbors and peers, financing or access to credit, greater economic empowerment (especially among women), and more future-oriented or health-risk reducing preferences. Masera et al. [49] emphasize the gradual nature of energy transitions and the phenomenon of technology stacking, while Lewis and Pattanayak [11] discuss several aspects that have received insufficient attention, including identification

[1] The literature discussed in this section was not identified using systematic methods, but rather emerged out of a consultative process used to motivate the full systematic review that followed, and to establish its boundaries, protocols, and analytical structure. As a starting point for these consultations, two of the study authors (Usmani and Pattanayak) developed a directed reading list, and presented potential approaches and framings to the full group of researchers, who then also suggested key additional references that warranted consideration. Additional resources relevant for the framing here were also identified and added at later stages in the systematic review analysis, and therefore did not directly inform its design.

[2] Fetter [102] considers historical energy consumption between LMICs and high-income countries across a substantially longer period and finds somewhat stronger evidence for energy "leapfrogging," but still finds effects of limited magnitude.

Table 1
Contributions of prior similar reviews or systematic analyses of the drivers or impacts of energy transitions.

Author(s)	Main focus	Type of review[a]	Inclusion/exclusion criteria	Technologies considered	Use energy services lens (Y/N)?	Geographic focus	Impacts covered	Drivers/ barriers? (Y/N)
Fluitman (1983) [35]	Review of the scale and impacts of rural electrification commissioned by the International Labor Organization (ILO)	Critical review (non-systematic)	Not discussed	Grid electrification	No	LMICs	Industrialization, mechanization, employment, income	No
Martinot et al. (2002) [36]	Considers donor and public efforts to promote and sustain investment in renewable energy, with a focus on enabling policies and business models	Critical review (non-systematic)	Not discussed	Renewable solutions	Yes	LMICs	n.a.	Yes
Cabraal et al. (2005) [37]	Review of literature on productive uses of energy in rural areas	Critical review (non-systematic)	Not discussed	All energy technology	Discussed, but not an organizing principle	Rural LMICs	Agricultural productivity, income, human capital	No
IEG (2008) [38]	Review of the economic benefits of rural electrification based on World Bank studies	Critical review (non-systematic)	World Bank evaluations of rural electrification investments	Electrification	No	Global	Energy use, education, health	To some degree
Bernard (2010) [39]	Review of rural electrification efforts and their outcomes from 1980 to 2010	Critical review (non-systematic)	Not discussed	Grid electricity	No	Sub-Saharan Africa	Health, education, income	To some degree
Ozturk (2010) [40]	Survey of literature linking energy and electricity consumption and economic growth and problems of causality inherent in these analyses	Critical review (non-systematic)	Bivariate models or multivariate models aiming to establish causality	n.a.	No	Global	National GDP or GDP growth	No
Sovacool et al. (2012) [41]	Conceptual piece—supported by empirical evidence—that calls for moving beyond clean cooking and electricity to a conception of energy poverty informed by energy services; highlights issues like mobility and mechanical power	Critical review (non-systematic)	Not discussed	n.a.	Yes	LMICs	Poverty	No
Sovacool (2012) [42]	Review of major consequences and harms of global energy poverty, and the structural features that maintain it	Critical review (non-systematic)	Not discussed	n.a.	No	LMICs	Development, health, gender empowerment, environment	Yes
Lewis & Pattanayak (2012) [11]	Study of the determinants of fuel and stove choice	Systematic review and vote counting	Multivariate regression analyses only; lack of comparable measures	Improved cookstoves and clean fuels	Cooking only	LMICs	n.a.	Yes
Bhattacharya (2012) [43]	Commentary on the relationships between energy access and development, with a focus on multiple dimensions of sustainability	Critical review (non-systematic)	Not discussed	Electrification and clean cooking	No	LMICs	Economic development	To some degree
Azevedo (2014) [25]	Considers evidence on—and drivers and welfare implications of—the energy rebound effect, i.e., how efficiency measures that reduce energy service costs free up resources for other uses—of the same good or others that require energy	Critical review (non-systematic)	Not discussed	Energy efficiency technology	No	Mostly high-income countries	Welfare impacts	Yes
Menegaki (2014) [44]	Meta-analysis of 51 studies linking energy consumption and GDP growth, which considers sensitivity to methods,	Meta-analysis	Included based on keywords: "energy consumption and GDP growth";	n.a.	No	Global	National GDP or GDP growth	No

(*continued on next page*)

Table 1 (*continued*)

Author(s)	Main focus	Type of review[a]	Inclusion/exclusion criteria	Technologies considered	Use energy services lens (Y/N)?	Geographic focus	Impacts covered	Drivers/ barriers? (Y/N)
	data, and variables included in regression models		excluded if lacking key variables					
Puzzolo et al. (2016) [12]	Assessment of the evidence on factors that enable or limit adoption and sustained use of clean fuels, and lessons on equitable scaling up of cleaner cooking fuels	Mixed methods systematic review	Inclusion of at least 1 of 4 clean fuels; empirical; LMIC interventions. Excluded studies that did not consider adoption, and studies in refugee camps	Clean household fuels	Cooking only	Africa, Asia, and Latin America	n.a.	Yes
Peters & Sievert (2016) [15]	Considers the impacts of electrification on various outcomes in Africa; reflects on differences in results relative to Latin America and Asia	Literature review and review of IE evidence	IE evidence is from rigorous evaluation studies	Electrification (grid and off-grid)	Discussed, but not an organizing principle	Africa	Energy use, income, education, health	No
Bonan et al. (2017) [13]	Review of "rigorous" evidence on the barriers and drivers of energy access, and its impacts on development and poverty reduction outcomes	Critical review (non-systematic)	Experimental and quasi-experimental studies that address selection on unobservables	Electricity connections; improved cookstoves	Discussed, but not an organizing principle	LMICs	Household outcomes (time, labor, health, income, welfare)	Yes
Bos et al. (2018) [14]	Review of challenges to and benefits of expanding grid electricity, focused on rigorous impact research	Critical review (non-systematic)	Highlight studies with rigorous IE methods, but do not exclude other studies	Grid electrification	No	Africa	Energy use, education, time use, health, business activity, migration	Yes
Burke et al. (2018) [45]	Review of macro-level evidence on role of electricity in development, including case studies; discusses causal identification problems in this literature, relative to micro-economic literature	Critical review (non-systematic)	Not discussed	Electrification	No	Global	National GDP or GDP growth	No
Morrissey (2019) [16]	Critical examination of the literature on electrification and productive use that increases incomes or creates opportunities for savings. Also considers the need for complementary services and heterogeneity across contexts.	Critical review (non-systematic)	Focus on studies of large-scale electrification that addressed selection issues	Electrification	Focus on income generation	Global	Productive use	No
Lee et al. (2020) [46]	Review of selected studies on the impacts of household-level and historical rural electrification initiatives	Critical review (non-systematic)	Focus on studies that use experimental and quasi-experimental methods	Electrification	No	Global	Labor, education	No
Bayer et al. (2020) [47]	Review of impact evaluations of household electrification programs	Systematic review	Studies that conduct statistical hypothesis tests of electrification impacts	Electrification	No	LMICs	Energy expenditure; Income and expenditure, savings, business creation, and education	No
This review	Study of the impacts of energy transitions and interventions	Systematic review	English language, quantitative studies	All energy technology	Yes	LMICs	Intra-household, household, public services, firms, national economy, and environment	No

Notes: We include only reviews that consider the drivers and determinants, or impacts, of energy transitions and interventions, and omit other reviews defining energy transitions or their dynamics. IE = impact evaluation. n.a. = not applicable.

[a] We follow the typology of reviews described in Grant et al. [48], which describes 14 types of reviews using a framework that considers the inputs and processes underlying different studies.

of the features of social marketing and behavior change campaigns that work best. Perhaps because such aspects are more difficult to study quantitatively, relatively few reviews address supply-side and institutional barriers and enablers; Lewis & Pattanayak [11] and Puzzolo et al. [12], and Barnes [50] are notable exceptions, for clean cooking and electrification, respectively. These reviews highlight the importance of standards, effective implementation and supply-chain development.

Reviews related to the impacts of energy transitions and technologies are somewhat less common than those concerned with drivers and determinants. Furthermore, most impacts reviews have been rather narrowly focused on emphasizing studies that apply particular methods (e.g., quasi-experimental or experimental impact evaluation designs, as in Bos et al. [14] or Bayer et al. [47]), and/or consider only a single type of technology in a specific context (e.g., grid extension to rural parts of Sub-Saharan Africa, as again in Bos et al. [14], and also in Peters & Sievert [15]). There is good reason for the former: in contrast to most correlational studies of drivers and determinants, the measurement of impacts demands careful causal attribution. Indeed, a particularly salient example of this attribution challenge in the energy impacts literature concerns the role of energy consumption in increasing national GDP, given the bidirectional relationship between these variables (comments above on the role of income in the determinants literature are also relevant here), including energy consumption from renewables [40,44,52,53]. The justification for a specific contextual focus, meanwhile, perhaps emerges from the reality that the appropriateness of different solutions varies across locations. As such, a broad focus makes it difficult to obtain insights, given the complexity and nonlinearity in the various pathways leading from enhanced "energy access" to impacts. And yet, comparisons across technologies and settings are valuable precisely because they provide a richer and more nuanced understanding of the role of energy in fostering development and environmental sustainability, and thereby help to inform better interventions.

With these comments in mind, it is worth noting that the most extensive review work of the consequences of energy technology development has considered the socio-economic impacts of rural electrification in sub-Saharan Africa [14,15,38,39]. This is where electricity connection rates are lowest in the world, and the reviews clearly aim to inform policy-makers about what they might expect to achieve with greater investments. Collectively, this prior work suggests rather muted impacts, at least in relation to the investment that is needed to achieve universal access [14]. For example, Peters & Sievert [15] argue that most estimates of large impacts from electrification (in terms of impacts on income and productive use, education and health benefits) come from studies conducted in Asia and in Latin America. They discuss a range of studies in rural areas in seven Sub-Saharan African countries that collectively point to only modest impacts, albeit over a relatively short evaluation period, and surmise that productivity benefits may only arise in more developed locations.[3] Additional studies reviewed by Bernard [39] and Bos et al. [14] largely corroborate this evidence, though the latter also highlight gains in consumption (especially watching television), quality of life, time savings, and time reallocation to education and away from domestic chores. Differences relative to other contexts may emerge from myriad challenges. Rural African households often take up new connections slowly due to high connection costs or unsuitability of their home infrastructure [14], consume relatively small amounts of electricity [14,15], and already use renewable devices for lighting such that substantial in-house pollution reductions documented elsewhere do not materialize [15]. Decentralized renewable investments have generally been difficult to link to development impacts [36]. In addition, rural micro-enterprises are hampered by other barriers, especially poor market access [15]. The observation of no increase in firm creation and hence labor demand is also confirmed by Dinkelman [54] in South Africa, though this study does find an increase in female labor supply. In the absence of rising demand for labor (due to lack of firm creation), wages fall, and welfare effects are unclear.

In considering the impacts of energy access more generally, Bonan et al. [13] discuss how access to electricity can and has delivered positive impacts, but nonetheless point to several knowledge gaps even outside Sub-Saharan Africa. For one, little is known about which types of household energy appliances are most impactful; a few scattered studies mention refrigeration [55], or access to media [56,57]. Second, enhanced agricultural productivity, as enhanced by groundwater pumping and processing, is another channel that is often discussed in the electricity and development literature, though evidence for productive rural uses more generally is limited, which is again related to rural peoples' limited energy use [37]. Third, evidence for education and health improvements remains surprisingly mixed. Finally, Bonan et al. [13] judge that the evidence on the impacts of improved cooking technologies is even weaker, pointing to the paucity of rigorous evaluation studies that have measured significant impacts on objective health outcomes [58], and contradictory findings regarding even time savings, e.g., in Beltramo and Levine [59] vs. Bensch and Peters [60]. They attribute the dearth and inconsistency in such results to both technological shortcomings, and to behavioral aspects of cookstove use, comments that are echoed in more general discussions about the lack of sustainability of many energy interventions [43]. Both the monocausal lens that draws attention only to energy constraints (rather than needs for complementary goods and services), and an inattention to behavioral aspects especially related to adoption, may be at issue in these impacts ambiguities [16,61].

The comments above help to highlight several features that make the present review unique relative to the prior literature. First, as highlighted in Table 1, this review focuses on a broad set of impacts of energy technology or interventions and thus provides a holistic look on their effects on human well-being and the environment. Specifically, it facilitates mapping of both positive and negative impacts of energy where they occur, since energy does not appear universally enabling of development opportunities, and is sometimes polluting. Indeed, this review includes both traditional and modern energy technologies to more clearly illustrate this point. Second, in mapping impacts across energy services (rather than technologies), this review reveals where evidence for the benefits that people actually obtain from energy is strongest, and where it is weaker or speculative. Here, an energy technology should be viewed as potentially enabling the use of energy services, rather than an end in and of itself. Third, unlike other reviews, this one includes studies from all three major LMIC regions (Asia, Latin America, and Sub-Saharan Africa), and bridges what is a common divide between electrification and cooking. Fourth, unlike other reviews that use unclear search and inclusion procedures, this one is based on a repeatable search algorithm, and has generated a large searchable database of articles that could be further analyzed, or updated, to provide more detailed analyses with specific regional, technological, methodological, or energy service perspectives. Overall, these features enable a deeper understanding of research on the role that access to modern energy plays in economic growth and development, which also serves to highlight outstanding gaps in the literature, and to motivate a cohesive research agenda that speaks to those gaps.

[3] The studies cover a range of technologies ranging from pico-photovoltaic and solar home system technology to mini-grids and grid electrification.

3. Material and methods

This review—carried out in 2017—proceeded in three phases: (i) Design of the framework with which to characterize identified studies; (ii) design of the search protocol and inclusion/exclusion criteria that capture relevant studies from the literature; and (iii) coding of each study in line with this framework to facilitate analysis and synthesis.

3.1. Energy services and end user framework

As noted in Section 2, ours is by no means the only systematic review that hones in on the human dimensions of energy, nor is it the only one that explores the literature on energy and development. One of its key distinguishing features, however, is the development and application of an "energy-services" and "end-user" framework with which to code and categorize studies.

This framework conceptualizes demand for energy by end users as driven by a desire to cater to specific energy needs. It emerges from a growing realization among applied social scientists that key energy end-users (such as households) rarely rely exclusively on a single energy technology (such as a clean-burning stove) or mode of energy provision (such as electricity from the grid) to meet all energy-using tasks. For instance, a rural household may use dirty biomass fuels in inefficient traditional stoves when preparing its main meals of the day, a rice cooker powered by electricity delivered by the grid exclusively to prepare rice, and clean-burning LPG to boil water multiple times over the course of the day for tea. At the same time, distinct energy technologies can also provide multiple energy services. In addition to their use for cooking, for instance, open flames and traditional stoves may also heat homes; households are likely to consider these secondary benefits when making energy-use decisions. Differences in energy-use patterns may, therefore, arise due to differences in end users' preferences (over food taste, cooking speed, or convenience), availability of fuels (such as fuelwood or electricity), as well as availability of energy technologies (such as different types of stoves) [62]. A framework that focuses only on energy technologies is unlikely to capture fully how end users ultimately use energy, and of the consequences of these choices for a range of societal outcomes [8]. Consequently, taking stock of the literature through such a lens will also offer a limited view of the state of knowledge.

Structuring the review around energy services—cooking, heating, cooling, lighting, appliances for consumption, agricultural production/income generation, non-agricultural production/income generation, and transportation—better reflects end users' own energy-use patterns. To understand the impacts associated with the energy-use patterns driven by these services, this framework is complemented by a simultaneous focus on impacts for different types of end users located across multiple domains that span across very different scales: intra-household, household, public services, firms/businesses, national economy, and the environment. As shown in Fig. 1, this enables a joint mapping of (i) which energy services have received relatively more (or less) attention in the literature; and (ii) which sets of end users or domains have received more (or less) attention. Appendix A presents additional details on this approach; here we also note that coding articles in the literature according to this framework requires careful work as many articles are not written with an end-use perspective in mind.

3.2. Review protocol and inclusion/exclusion criteria

The search protocol was designed with three guiding principles in mind:

(1) Relevance: Based on prior literature, a search protocol was constructed that combined three types of search terms (Appendix Table A2). First, key impact categories (e.g., health, education, income growth) that would be of concern to both research and practitioner communities. Second, technology-specific terms (e.g., solar technologies, cookstoves, grid electricity). Finally, a list of all low- and middle-income countries (as defined by the World Bank) and regions.[4]

(2) Breadth: Cognizant of the fact that relevant research may be missed by these targeted search terms, the search protocol was structured to allow for permutations and combinations of each of the initial terms (e.g., solar and health, solar and education, solar and income growth). Additionally, embedded into the three search groups were a variety of broader terms (such as "energy transition" or "sustainable energy" in the technology category, country-grouping or continent terms in the list of countries, or general terms like "impact" into the list of impact types) to capture remaining studies that might have been missed by more specific keywords. Thus, a wider net was cast at the outset of the search, which allowed for narrowing to relevant literature in subsequent phases.

(3) Replicability: The search protocol was implemented in two scholarly databases: Web of Science and EconLit. Although these databases require search terms to be structured in specific ways, the division of terms into three broad categories—namely, into technology, regions, and impacts, as shown in Table A2—is meant to provide researchers looking to replicate and modify the basic search with the means to do so conveniently.

The search was conducted in the Web of Science Core Collection in January 2017, and yielded over 70,000 results. It was then repeated in EconLit, from which approximately 10,000 papers were obtained. Accounting for duplicates across the two sets of results yielded an initial sample of 79,138 studies, all of which were screened for relevance to identify the subset relevant to the review.[5]

The inclusion/exclusion criteria guiding the screening were designed to restrict the sample of coded articles to those considering the *human* dimensions of energy—that is, papers that addressed how energy interacts with, influences, and impacts individuals and societies—rather than literature which applies a technological lens. For example, a study that outlines the design of a new cookstove and highlights that it has been found to be effective at reducing smoke emissions in laboratory settings would be excluded as it fails to engage with the human dimensions of energy use in meaningful ways. A study that finds that such a device reduces household air pollution levels in an experimental intervention conducted in a remote, rural setting would be included. More precisely, studies were judged to be germane to the review and coded in full detail if they were:

(1) Focused on the human dimension of energy use, broadly defined to include studies that examine the drivers of uptake of energy services/technologies, and/or those that evaluate impacts of energy services/technologies;
(2) Quantitative: Econometric or statistical analyses, cost-benefit analyses, life-cycle assessments, non-economic modeling, simulations, and financial analyses were included[6];

[4] Restricting the search to developing countries only can potentially create a biased sample. Indeed, there may be something about today's low- and middle-income countries that has caused them to not have high incomes (yet), and this may be systematically related to energy-use patterns. In finalizing the search terms, we explored the consequences of excluding geographic terms, and found that this inflated the number of search results by a factor of roughly two. For logistical reasons, the developing-country identifiers were retained.

[5] Specifically, 1,657 studies were found in both scholarly databases by these searches.

[6] Papers that were exclusively qualitative but still focused on energy and development were tagged as such, and information on their basic features (such as country/region, journal names, and publication dates) was recorded.

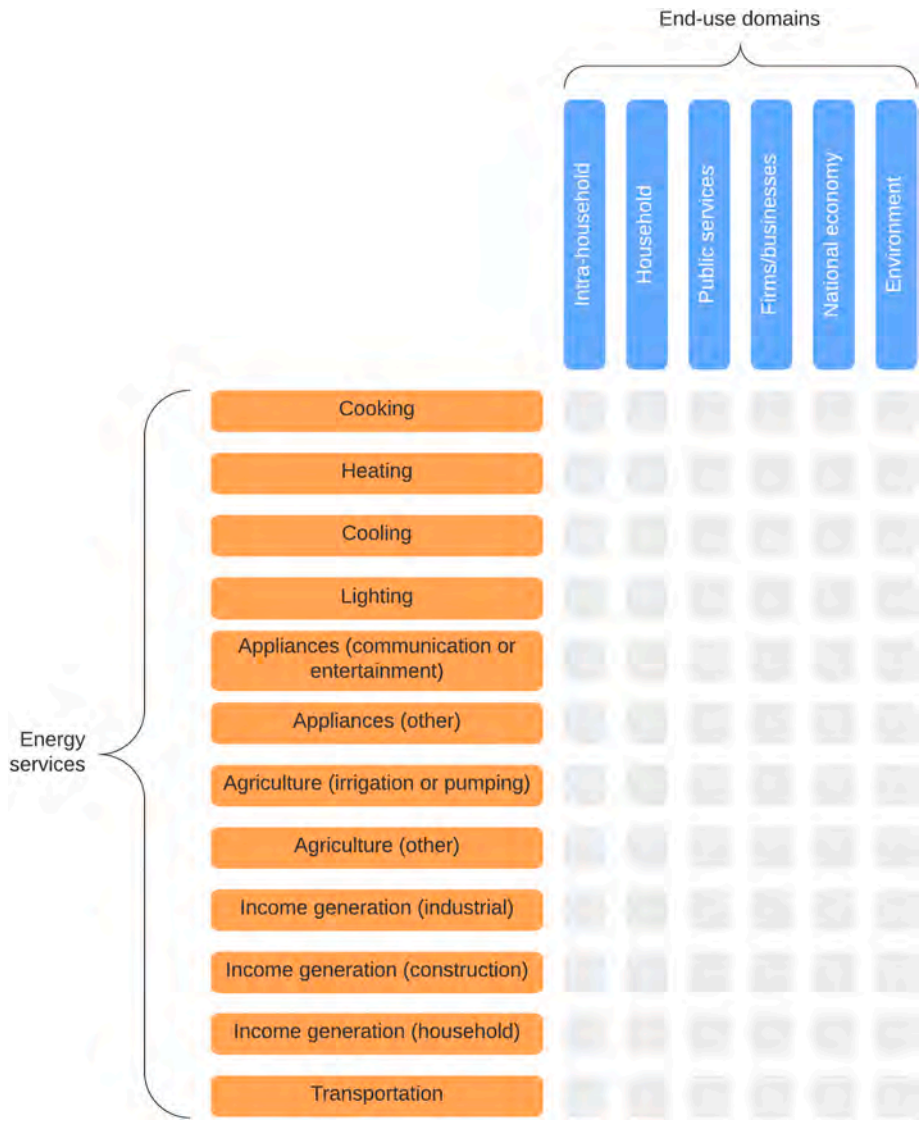


Fig. 1. Energy services and end user framework.

(3) Primarily focused on low- and middle-income countries in their analyses[7] and
(4) Published in peer-reviewed English-language academic outlets.

Studies were not excluded based on chronological thresholds (e.g., restricting to studies published after 1992), nor because they focused on a particular unit of analysis (e.g., only household-level studies). The last criterion, peer-reviewed and English-language publication is important because there is a great deal of grey literature that offers rich insights on energy–society interactions that is not peer-reviewed. Similarly, there are likely many relevant articles written in non-English language outlets. Though the perspectives in these literatures are undoubtedly important, there are obvious practical hurdles to including them, related to replicability in coding and searchability of non-English language databases.

3.3. Coding procedure and quality control

The coding procedure began with random assignment of the nearly 80,000 studies to a team of graduate research associates, for inclusion/exclusion and detailed coding. Random assignment prevented systematic differences in coding ability or prior familiarity with energy-related themes from affecting the final dataset. To evaluate the relevance of a particular study (in line with the inclusion/exclusion criteria outlined above), coders began by closely reviewing its title, abstract and journal.[8] For each study gauged to be relevant, coders conducted a detailed review of the full paper, extracting the following information[9]:

(1) Basic study characteristics: Setting (such as country or region), unit of analysis (e.g., individual-level, household-level, etc.), study type (e.g., econometric/statistical analysis, non-economic modeling, financial analysis), empirical technique (e.g., experimental, quasi-experimental), and sample size;

[7] Studies could consider multiple countries and if they did, were coded as regional or according to the countries included.

[8] Where the title, abstract and journal did not provide sufficient information to gauge the relevance of a particular study, coders engaged in a scan of the full paper.

[9] Papers that could not be accessed by coders were tagged as such. Upon completion of the coding process, we returned to this list of approximately 800 inaccessible to attempt to retrieve them once again, and were successful with about half of them. Approximately 450 papers remained inaccessible.

(2) Main topic or technology (e.g., biogas, grid electricity, improved or transitional cookstoves);
(3) Whether the study evaluated drivers and determinants of the energy technology in question;
(4) Energy services covered by the study (e.g., cooking, lighting, communications, etc.);
(5) Impacts, if applicable, across a variety of domains and end users (e.g., households, firms, economy); and
(6) Broad characterization of the size and direction of impact, if applicable (e.g., positive and statistically significant, negative but not statistically significant, unclear). In statistical studies, significance for an impact indicator (the dependent variable) was assessed based on *t*-tests comparing observations with and without access to the energy technology/intervention, or from a regression coefficient on the energy access variable of interest (specifically the *p*-value for rejecting the Null hypothesis that the effect of energy access was equal to zero).

Quality-control steps were included before, during and after the coding process to ensure consistency of the contribution being made to the final dataset by each coder. Prior to starting, each coder attended at least two training workshops and engaged in multiple rounds of practice coding with a predesigned coding template in order to foster a consistent understanding of the aims and scope of the review. This coding template—which itself had undergone multiple rounds of piloting—was designed to be sufficiently restrictive to ensure consistency in responses, while allowing coders to convey study-specific nuances or idiosyncrasies as needed. For example, for studies that conducted an impact evaluation, coders selected the size and direction of the study's result using drop-down menus but also had the option of adding additional details if they deemed it necessary. These additional notes were reviewed by one of the authors of this paper.

At several points in the coding process, which began in February 2017 and was completed in December 2017, refresher trainings were conducted with coders to evaluate progress, and obtain feedback about challenges they were facing with the coding process. In addition, coders had the option to tag a particular study as "requiring additional review" during the coding process. These studies—approximately 200 in all—were reviewed and coded a second time by one of the authors, and the results compared with those of the original coder.

In addition, ten percent of the initial search sample (approximately 8,000 studies) were randomly assigned for double coding so as to enable *ex post* validation of coding consistency. These were evaluated on the basis of consistency of i) coders' decisions to include/exclude a particular study, and ii) the more detailed coding of study characteristics, conditional on agreement on relevance across those two coders.[10]

The final element of review and quality control of the systematic search and coding process was provided by collecting feedback from a broader network of collaborators who are members of the Sustainable Energy Transitions Initiative (SETI). At the onset of the work, in late 2016, these researchers provided input on the search terms, inclusion/exclusion criteria and scope of the review, and coding structure (including specification of energy services and impact domains). They then reacted to initial results and descriptions of the dataset at three separate moments, helping to guide decisions related to adjustments to the process (May and October 2017, and May 2018).

[10] Examining these 8,000 studies, coders agreed on whether a particular study was germane to the review or not approximately 90% of the time. Average consistency rates in coding study characteristics (such as sample size and region) (80%), services (89%), and basic impacts (97%) were generally high, with no systematic differences in inconsistency rates identified across members of the coding team.

3.4. Limitations

This review has three main limitations. First, given its broad scope, it cannot identify key concepts that neatly categorize every single study identified by the search protocol. This risk was partly mitigated through extensive consultations with SETI network researchers, who helped guide the definition of topics at the heart of the review's conceptual framework, in ways that enhanced its inclusivity and policy relevance. Multiple trainings with coders subsequently helped increase consistency in interpretation, lowering coding errors and leading to more uniform interpretations of the evidence. Nevertheless, "blind spots" (such as specific topics or sub-regional focuses) unaddressed by this review likely remain.

Second, the review's focus on quantitative approaches and methods incompletely characterizes the broader social science literature on energy access. As described earlier, the search and coding protocol focuses on econometric/statistical analyses, cost-benefit analyses, life-cycle assessments, non-economic modeling, simulations, and financial analyses. Other scholars identify somewhat different sets of social science methods that do not always overlap perfectly with those in this review and that may not have been systematically captured [63]. Alternatively, some reviews choose to focus on very narrow set of methods, which generate more uniformity and comparability in their results, e.g., allowing inclusion only on the basis of applying a specific statistical model.

Finally, this review cannot comment on the rigor of included studies as it does not conduct assessments of the quality of individual works. Gauging study quality and excluding literature based on quality criteria poses unique challenges (such as requiring different methods to be evaluated against one another hierarchically) that are somewhat inconsistent with one of the main objectives of this exercise: to take stock of a scattered and disconnected literature on the impacts of energy transitions on society. Rather, this review highlights topics, methods and geographical regions that have (not) received attention in the energy-access domain. In so doing, it seeks to orient future research efforts to meet policy needs on the ground.

4. Results

4.1. Summary of included articles and themes

4.1.1. Categorization of articles according to methods, energy services, and technology

About 8,000 studies (or just over ten percent of articles identified by the search algorithm) were deemed "relevant" given the aims of the systematic review during initial screening; the 7,693 of these papers—which were both qualitative and quantitative—that were accessible were then coded further. The low rate of inclusion from the 79,138 studies first identified in the search suggests that we were successful especially in ensuring that our terms were not overly restrictive: that is, the search captured many more articles than were deemed relevant. Importantly, in early pilot testing with various permutations of search terms, combinations that yielded a relevance rate of approximately ten percent appeared to capture the right breadth of articles and were successful in identifying key and well-known papers in the literature.

Owing to the differences in methods required for analysis of relevant qualitative papers (n = 3,379), these are not discussed further. We instead begin with a descriptive summary of the coverage of the remaining 4,314 quantitative articles. Fig. 2 outlines the breakdown of the final sample of these articles, across four distinct categorizations: study type, empirical design or approach, energy service, and technology type.[11] An individual paper can be categorized as representing more

[11] Cross tabulations showing the overlap between energy services and study type or technology categories are provided in Appendix Table B1.

than one study type or include more than one energy service, but the empirical design sub-categories are mutually exclusive. As shown, just about half of the reviewed studies include econometric or statistically-based analyses. Studies also commonly incorporate economic (19%) or non-economic (26%) modeling approaches. The empirical methods used are overwhelmingly observational (74% of studies); 19% do not include empirical analysis. Quasi-experimental, experimental, or natural experimental evaluation designs are rare, representing less than 10% of all quantitative studies, and there is no clear upward trend in the relative percentage of such studies over time. Absolute numbers of more rigorous published evaluations each year did increase by a factor of 4.7 between 2001 and 2017, however, which is similar to the overall increase (by a factor of 4.6) in all quantitative scholarship. While observational studies often provide useful insights and should not be ignored, the paucity of more sophisticated quasi-experimental and experimental empirical designs points to a need for more rigorous assessment of the causal role of energy access in facilitating economic development.

The two most commonly considered energy services are cooking (28% of studies) and income generation linked to industry (20%), but lighting (17%) and heating (18%) are also commonly considered in the quantitative literature on energy in LMICs. Transportation and appliance uses are represented in 15% and 13% of studies, respectively; the least covered services are non-irrigation-related agriculture uses (7.1%), agriculture water pumping (6.1%), and household income generation (5.6%). Finally, with respect to technology, about 32% of studies deal with cooking technology, either traditional (20%) or improved (12%). Next, 31% of studies do not pertain to specific generation or distribution options, but 20% consider energy aspects related to the grid. Among renewable options specifically, solar (7.9%) receives the most attention, followed by hydro, biogas, and wind. The observation that solar attracts more attention than wind in the quantitative social science literature may stem from the fact that wind turbines are more commonly installed at utility scale than at a household scale, though total wind global capacity reached 433 GW in 2015, almost twice that of solar.[12] Given its greater deployment as a household-scale generation, solar, especially as an off-grid solution to rural electrification, may have more direct implications for health, education and household income as measured using survey evaluation methods.

4.1.2. Coverage of articles by time of publication, geography, and journal

Fig. 3 highlights the temporal (panels *a* and *b*) and geographical distribution of relevant studies distinguishing the country distribution of those employing any quantitative approach (panel *c*), or only econometric or statistical techniques (panel *d*). Though energy access issues are hardly new, there has been a recent surge in scholarship on the topic. The share of quantitative papers has also increased. Compared with fewer than 50% of studies in 2010, quantitative papers accounted for more than 60% of those that we determined to be relevant in 2016 (see Appendix Figure B1 for additional detail on trends over time for subgroups of papers, e.g., by study type or energy service). A general path toward green development and emphasis on "energy justice" that followed the global financial crisis and economic recession, along with rising consensus around the urgency of anthropogenic climate change and the discussions that culminated in the United Nations SDGs, may have facilitated a sudden increase in attention to energy topics [64–66]. In June 2009, for instance, ministers from 34 Organisation for Economic Co-operation and Development (OECD) countries declared that they would "strengthen their efforts to pursue green growth strategies as part of their responses to the crisis and beyond, acknowledging that green and growth can go hand-in-hand" (OECD 2011). Meanwhile, increasing awareness of climate change and the importance of emissions from developing countries, especially Brazil, Russia, India, and China (the so-called "BRIC" nations), has led to large investment in renewables. Many studies during this period examine the relationships among economic growth, energy consumption and emissions or environmental pollution [67–69]. Also consistent with the emergence of SDG7 with its inclusion of electricity access and clean cooking, papers increasingly consider improved cookstove interventions [70,71] and off-grid electrification efforts [72,73]. Meanwhile, global air pollution problems have become ever more salient, stimulating work on issues related to its drivers and impacts, especially in China [74,75].

Over 1,000 studies—about a quarter of all relevant quantitative studies—focus entirely or partly on China, which is roughly proportional to its share of LMIC country population. India, the next most studied country, is the focus of approximately eleven percent of relevant studies, well below its relative population share (Fig. 3, panel *c*). Save for Kenya, Nigeria, and South Africa, work on energy and development in Africa remains sparse. Indeed, several African nations do not appear to have a single quantitative peer-reviewed study that investigates an energy-related question. This broad trend also holds when one examines only the studies that employ econometric or statistical techniques (Fig. 3, panel *d*). With respect to technology (distributions not shown), there is more even geographical balance among solar studies than others, a primary focus on large and richer countries (e.g., South Africa, Nigeria, India, Turkey, and China) for grid electricity, and greater concentration on cooking, especially improved cookstoves, in China, India, and East Africa. Further below in Section 4.3, patterns as a function of development levels are considered in greater detail.

Studies examined in this paper come from nearly 846 different journals, spanning energy, economics and policy, public health, and many other domains. Although economic theory has much to say about household energy consumption behaviors, most papers are published in policy-oriented journals. The Herfindahl-Hirschman Index (HHI) based on the share of the articles published in each journal is 304, indicating low concentration in general.[13] The most common academic journals in which relevant articles are published are *Energy Policy* (14.1%), *Energy* (5.1%), and *Applied Energy* (3.9%). Five out of the other 10 most common journals focus on sustainable energy: *Renewable Energy* (3.9%), *Journal of Cleaner Production* (2.5%), *Atmospheric Environment* (2.4%), *Energy for Sustainable Development* (2.1%), and *Biomass & Bioenergy* (1.7%). *Energy Economics* (2.9%) is the only economics journal that appears in this list of ten most common journals (Appendix Table B2 presents a longer list).

4.2. Evidence gap maps for the energy services to impacts literature

Of the 4,314 quantitative articles identified and coded in this review, 3,020 (70%) report on at least one type of impact from energy or energy technology, as classified according to our major domain or end user categories. Table 2 shows a cross-tabulation with the number of studies that address each impact category or subcategory (in the columns), by service (in the rows).[14] Darker colors show service–impact combinations where research studies are concentrated. Considering first the more micro-level (or highly local) domains, we see that reported impacts on household health (the most common impact category considered at the household level, included in nearly 43% of such studies) predominantly cover cooking (Panel A). Studies of other services that consider health

[12] Renewables 2016, Global Status Report. http://www.ren21.net/wp-content/uploads/2016/06/GSR_2016_Full_Report.pdf.

[13] Here, HHI is a measure of the relative share of individual journals among all of the journals in which studies on sustainable energy transitions are published. When used in industry analysis (measuring market shares of individual firms in an industry), an industry is considered competitive if HHI < 100, has low concentration if $100 <$ HHI < 1500, moderate concentration if $1500 <$ HHI < 2500, and has high concentration if HHI > 2500.

[14] In the supplement to this article, we also provide a complementary perspective on impacts that focuses on technology type rather than energy service (Table B3).

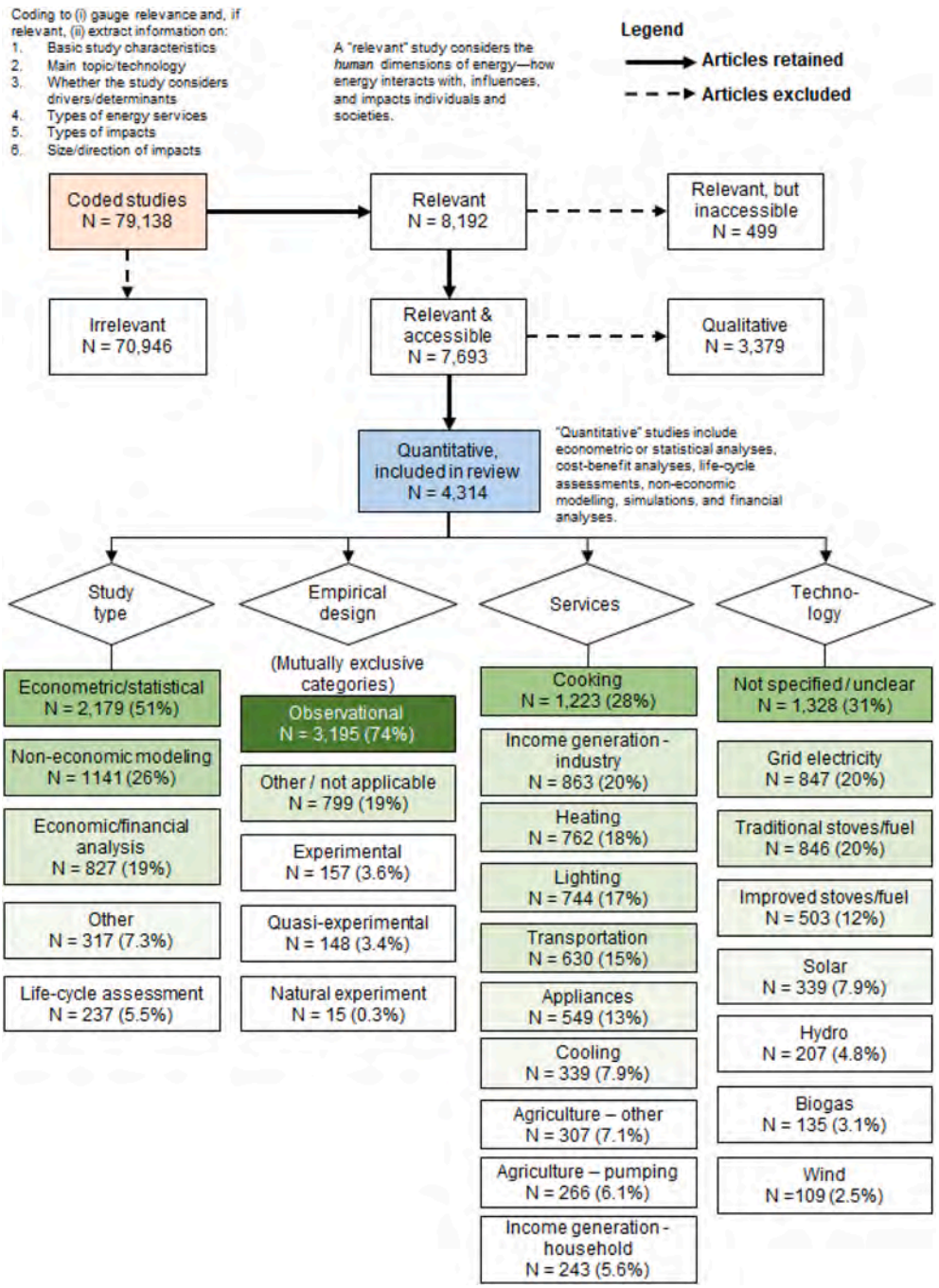


Fig. 2. Breakdown of quantitative articles included in the review, according to study type, empirical design, energy service and technology. [Notes: Inaccessible articles had titles and abstracts online but were not available in the public domain. Total percentages may exceed 100% for each of the four sub-branches except empirical design, under which the sub-categories are mutually exclusive. Darker greens indicate a greater proportion of studies. Not specified/unclear under technology encompasses general energy papers that do not differentiate across technologies.].

impacts represent only a fraction of these (next most common are heating, with about one-third the number of studies for cooking, and lighting, with about one-sixth as many). In comparison, household-level impacts on consumption and expenditures, the second most common impact considered at this level (in 32% of such studies), are more evenly spread across services. Income and attitudinal impacts (considered in 19% and 10% of household studies, respectively) are similarly relatively evenly distributed across services. Intra-household impacts are much less frequently analyzed (in only 65, or 2.1% of studies), as are changes in time allocation (88 studies), education (47 studies), and demographic/fertility (36 studies) responses.

Moving to other impact domains, but still at the micro level, there is a dearth (only 50) of public service impact studies (Panel B). Among these, lighting is the most commonly considered service, followed by appliances (no other service is represented in more than ten studies). The lack of studies on the value of cooling (e.g., cold chain for vaccines, refrigeration of essential and heat-sensitive medicines) and energy for treatment technology (appliances in health) points to a gap related to essential inputs to health care. Among studies of firm-level impacts, which are far fewer than those for households, the greatest focus is on industrial/manufacturing productivity—many such studies are national scale analyses in middle-income countries where these sectors are more developed [76,77]. The commercial services sector is underrepresented, despite the importance of cooling services for commercial, food and beverage-related businesses, the need for reliable electricity for many communications and transactional needs, and so on. Of the 208 national-scale impact studies reviewed here, 189 (91%) consider impacts on income or Gross Domestic Product (GDP; other indicators of national development are infrequently considered); these are also relatively evenly spread across energy service types, again with a tilt

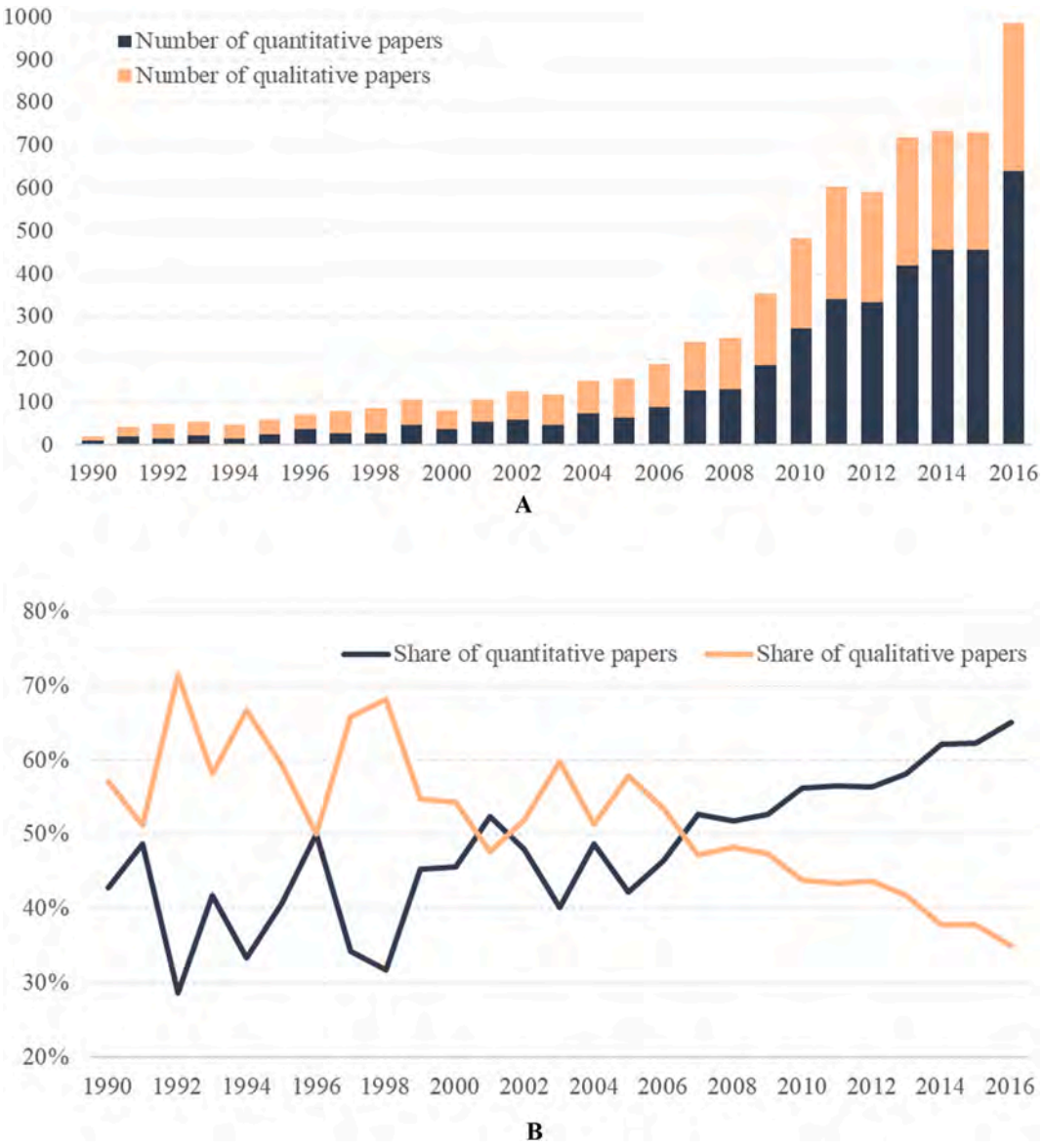
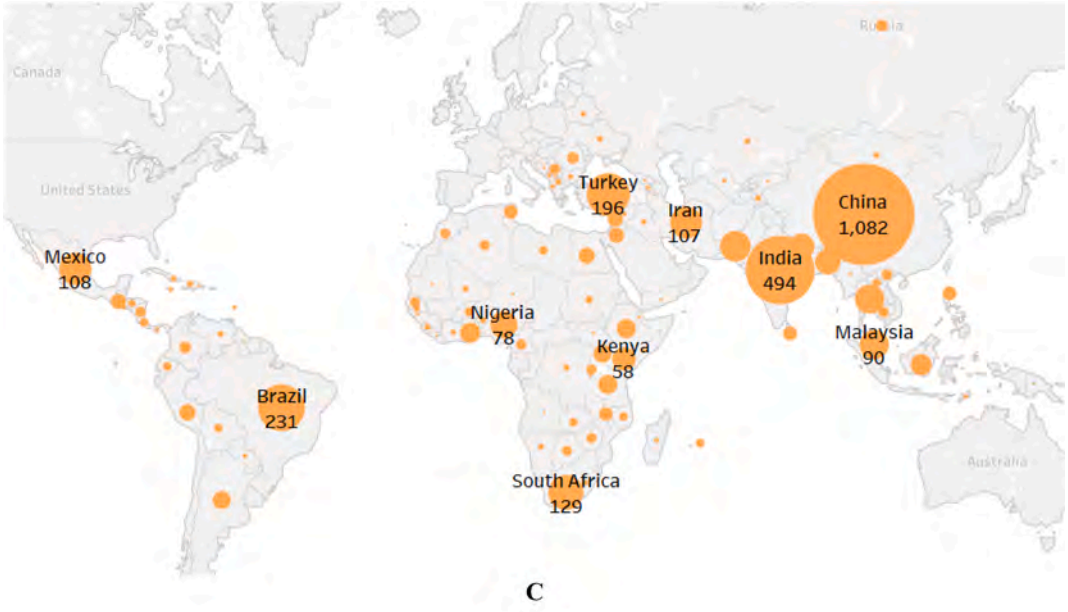


Fig. 3. Distribution of studies over time and by country [Notes: Panels A and B include all quantitative and qualitative studies in LMICs; Panel C displays the geographic distribution of all quantitative studies in LMICs. Panel D shows the distribution of the 2,179 studies identified specifically as "econometric/statistical", in which country focus was identified for 1,854].

towards large-scale industrial productivity.

Finally, in the environmental domain, where the scale is often broader, air quality and climate-forcing emissions dominate. Here there is also overlap with household studies in that a concentration of scholarship pertains to cooking services, which reflects dual environmental and health concerns associated with cooking practices, and the fact that micro-concerns and methodologies still drive much research on larger scale environmental quality problems. However, additional services are also comparatively well represented (most notably transportation, industrial/manufacturing productivity, lighting, heating, and consumer appliances). The environmental impacts of agriculture and productive services other than industry are rarely a focus. Similarly, impacts on forests, local ecosystems, and especially energy materials pollution, are less common. The lack of evidence in the former two sub-domains has previously been discussed [78].

The relative imbalance in the number of cooking studies focusing on health relative to other impacts is striking, considering that the costs and benefits of cooking services have been shown to be sensitive to pecuniary costs of alternative stoves and fuels as well as implications for time allocation [7,78]. All of these are hypothesized to affect attitudes, consumption/expenditures, and productivity. To be sure, behavioral aspects related to cooking appear understudied relative to health. Services that have low representation in the literature are cooling, agricultural production, household income generation, and transportation. The paucity of work on agricultural production is also striking since the livelihoods of many households in lower-income countries, especially in rural contexts, heavily depend on agriculture.



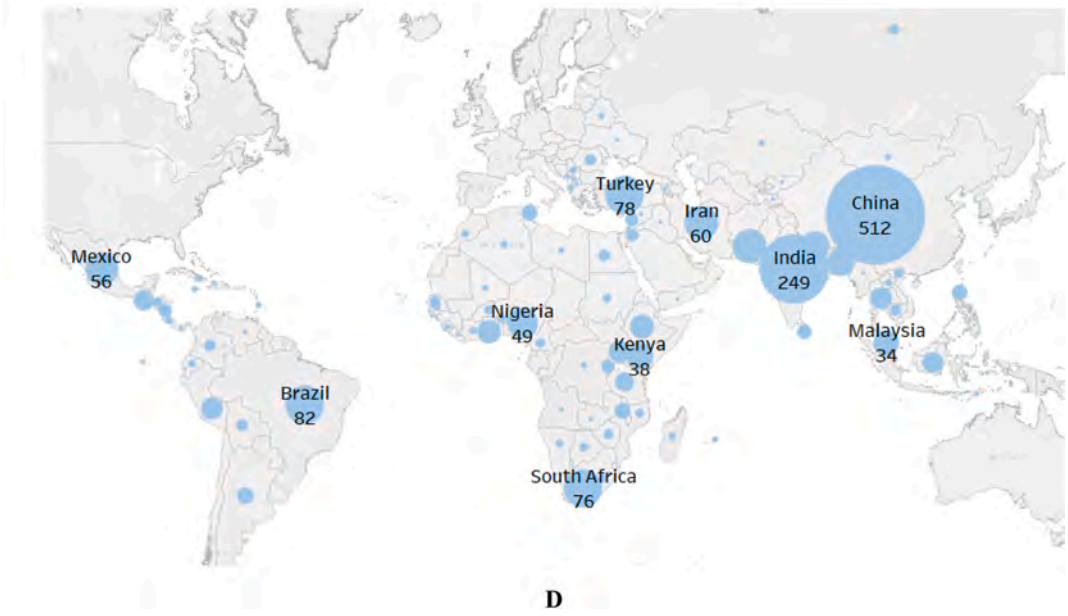


Fig. 3. (*continued*).

4.3. Alignment of measured impacts and services with development objectives and energy transitions positions

Section 4.2 provided a detailed look at research on impacts according to energy services; the nature and consistency of evidence on those studied impacts are considered here. Mapping specific impact categories to other Sustainable Development Goals that are most clearly linked to energy access helps to clarify these patterns (see Table 3 for the organization of this mapping), illustrating the direction of the relationships between different impact indicators and energy technology or interventions. As also described further in Section 4.4, apparent inconsistencies often reflect heterogeneity across technologies (e.g., traditional cookstoves vs. improved cookstoves, or fossil fuel-based grid energy vs. decentralized solar energy), which implies that an analysis by technology rather than energy service is helpful as well. Inconsistencies on aggregate should not be interpreted as contradictory, since some relationships may be positive overall (e.g., clean cooking fuels and air quality), and others negative (e.g., traditional stoves and air quality).

Fig. 4 shows that the impacts of access to energy services in a variety of domains are not universally positive; i.e. the so-called "golden thread" of energy may not always be golden.[15] Each wedge—sized according to the number of studies included in it—of a single blue hue maps (according to the color-coding in Table 3) to an SDG in the innermost circle,

[15] In Appendix Figures B2-B5, we show analogous figures that disaggregate Fig. 4 according to country income groups (based on the World Bank classification of low-, lower middle- and upper middle-income countries), and also for the non-statistical (modeling, cost-benefit analysis (CBA), life cycle, or other) studies, in which statistical significance is not reported, only direction of impact.

Table 2
Distribution of areas of concentration and evidence gaps by service, among the 3020 coded articles (darker blues indicate areas of concentration). Panel A presents intrahousehold- and household-level impacts, Panel B presents those on public services, firms, and at a national scale; Panel C shows the environmental scale. Studies may cover more than one impact and more than one service, but the number of unique studies by impact or service category are shown in the "ALL" rows and columns, not the total counts.

Panel A

Services	Intrahousehold (n=65)	Household (n=1053)										Total count
	Gender	Health	Attitudes	Education	Demographics	Migration	Time Allocation	Income	Consumption/ Expenditures	Other	ALL household	
Cooking	55	361	39	27	26	8	71	84	111	15	574	797
Heating	12	107	19	11	8	6	19	45	98	8	251	333
Cooling	4	12	12	5	4	3	3	20	60	2	91	125
Lighting	14	53	53	23	13	4	20	89	169	12	322	450
Appliances- Communications or Entertainment	7	32	39	17	8	2	12	58	135	9	224	319
Appliances- Other	6	37	41	14	8	2	8	46	134	5	212	301
Agriculture- Irrigation or Pumping	2	9	7	5	1	1	3	14	29	3	52	74
Agriculture- Other services	4	12	7	3	1	2	6	14	20	6	48	75
Income Generation- Industrial	3	40	17	5	4	3	1	25	89	18	168	205
Income Generation- Construction	2	6	6	2	0	2	0	4	19	3	31	44
Income Generation- Household	3	11	9	5	3	2	6	40	25	7	75	111
Transportation	2	41	14	5	1	2	6	23	52	5	119	151
ALL services	65	451	108	47	36	11	88	198	341	56	1053	1401
Total count	**114**	**721**	**263**	**122**	**77**	**37**	**155**	**462**	**941**	**93**	**2167**	**2985**

Panel B

Services	Public Services (n=50)				Firms/Business Development (n=363)					National Economy (n=208)				Total
	Health Facilities	School Facilities	Other	ALL Public Services	Services	Manufacturing/ Industry	Agriculture	Other	ALL Firms	GDP	HDI	Other	All National	
Cooking	1	2	1	4	7	22	29	5	53	55	3	5	61	**130**
Heating	2	3	5	8	8	28	19	6	52	52	1	7	58	**131**
Cooling	4	4	2	7	6	21	6	6	34	45	0	3	47	**97**
Lighting	13	16	9	30	15	45	18	10	72	72	3	6	79	**207**
Appliances- Communications or Entertainment	7	10	4	14	11	40	14	5	55	61	2	4	65	**158**
Appliances- Other	14	10	4	20	12	40	15	5	55	60	0	5	64	**165**
Agriculture- Irrigation or Pumping	1	1	3	4	5	8	54	4	64	37	1	6	43	**120**
Agriculture- Other services	0	1	0	1	4	14	67	4	75	51	2	3	53	**146**
Income Generation- Industrial	3	1	6	9	28	157	24	8	190	139	1	12	146	**379**
Income Generation- Construction	1	0	3	4	5	12	3	7	20	38	0	5	41	**74**
Income Generation- Household	0	1	1	2	9	9	11	5	23	41	1	5	45	**83**
Transportation	0	0	4	4	3	13	27	4	42	63	1	8	68	**123**
ALL services	17	18	23	50	48	187	147	19	363	189	6	20	208	**674**
Total	**46**	**49**	**42**	**107**	**113**	**409**	**287**	**69**	**735**	**714**	**15**	**69**	**770**	**1813**

Panel C

Services	Environment (n=1465)							Total
	Air Quality	Forest	Ecosystems	Climate/GHG	Disposal of Energy Materials	Other	All Environment	
Cooking	345	111	52	211	4	7	584	**730**
Heating	158	49	40	189	9	5	348	**450**
Cooling	37	3	16	108	3	6	135	**173**
Lighting	96	21	55	255	17	5	324	**449**
Appliances- Communications or Ente	68	13	43	190	14	5	233	**333**
Appliances- Other	64	14	41	194	13	5	234	**331**
Agriculture- Irrigation or Pumping	10	3	22	59	1	7	82	**102**
Agriculture- Other services	29	9	26	89	2	5	120	**160**
Income Generation- Industrial	136	8	78	348	15	16	483	**601**
Income Generation- Construction	16	1	14	67	1	8	89	**107**
Income Generation- Household	17	7	17	64	0	6	92	**111**
Transportation	214	10	25	299	2	9	426	**559**
ALL services	644	139	167	850	31	33	1465	
Total	**1190**	**249**	**429**	**2,073**	**81**	**84**	**3150**	**4106**

but multiple indicators (e.g., air quality and personal health impacts) can be grouped together (e.g. within the good health and well-being SDG), as delineated in the second layer of the circle. The wedges are organized by size; that is, moving clockwise around the circle, the SDG mapping with the most impact evidence is followed by the one with the second most evidence, and so on. Across all statistical studies, the most evidence exists for health (both air quality and personal health indicators) and climate outcomes, but both of these show large proportions of negative impacts overall. Evidence related to the poverty alleviation goal (consumption, income and time use) is more consistently positive, followed by mostly negative evidence related to ecosystems and forest health. Energy has positive impacts on most of the other SDGs for which there is less evidence—GDP, manufacturing and services, agriculture, and education—except for gender empowerment.

Table 3
Thematic areas for identifying impacts within domains.

Domain/End user	Thematic area	Mapping to Sustainable Development Goal (for Fig. 3)
Intra-household	Gender	Gender equality (SDG5)
Household	Health	Good health & well-being (SDG3)
	Attitudes	n.a.
	Education	Quality education (SDG4)
	Demographics	n.a.
	Migration	n.a.
	Time allocation	No poverty (SDG1)
	Income	No poverty (SDG1)
	Consumption/expenditure	No poverty (SDG1)
	Other	n.a.
Public services	Health facilities	Good health & well-being (SDG3)
	School facilities	Quality education (SDG4)
	Other	n.a.
Firms/Business development	Services	Industry, innovation & infrastructure (SDG9)
	Manufacturing/industry	Industry, innovation & infrastructure (SDG9)
	Agriculture	Zero hunger (SDG2)
	Other	n.a.
Economy	GDP	Decent work & economic growth (SDG8)
	HDI	No poverty (SDG1)
Environment	Air quality	Good health & well-being (SDG3)
	Forest	Life on land (SDG15)
	Ecosystems	Life on land (SDG15)
	Climate/Greenhouse gases	Climate action (SDG13)
	Disposal of energy materials	Life on land (SDG15)
	Other	n.a.

In the next section, we dissect these patterns of evidence on impacts further, according to technology and services.

Also worth noting is that the depth and distribution of impacts studied varies considerably across country income categories, perhaps reflecting the varying importance of different energy services as a function of development, or their different energy access challenges and energy transitions trajectories. Relative to their shares of global population, upper middle income countries (UMICs) are overrepresented, with 56.1% of impact studies for 42.2% of global LMIC population; however, when considering overall energy use in these countries, they are underrepresented (Fig. 5). Both lower middle-income (LoMICs) and low income countries (LICs) are somewhat underrepresented by population, but not based on overall energy consumption (with 34.9% and 8.9% of impact studies, respectively). The impacts and services covered vary across these categories in ways that are consistent with energy use patterns and SDG priorities. For one, energy use in LICs is primarily for residential services demanded by households (Fig. 5), with industry and transport uses far behind, and household impacts and services are well represented in these poorest countries. Second, in LMICs and UMICs, energy consumption is considerably higher, and the relative sectoral balance shifts towards transport and industry, and especially the latter in UMICs, consistent with the services breakdown across country income categories. Third, energy services that are more clearly residential—like cooking—are primarily considered for their impacts on household outcomes in our breakdown of papers, while industrial income generation tends to be examined for its impacts at a larger number of levels, e.g., on both firms and households. Finally, while health and air quality remain the leading category across all three groups (Appendix Figures B2-B4), climate outcomes are much more studied in UMICs, relative to poverty alleviation outcomes in LICs and LoMICs. Not surprisingly, given their lower energy use, climate impacts are infrequently studied in LICs, but so are impacts on GDP and on firms (manufacturing, services, and even agriculture), which are studied less than gender equality and education. LoMICs and UMICs look more similar, though gender equality receives more attention in LoMICs. The impacts covered across these country income categories could also reflect differences in societal conceptions of what energy services are essential for a minimum standard of living. The conception of which energy services are customary for well-being differs across societal contexts; when societies grow richer their members escalate expectations of what constitutes energy justice [79]. To the extent that some energy researchers are motivated at least partly by notions of energy justice, this in turn informs the topics that researchers choose to study. With this lens in mind, it is instructive to consider the distribution of services studied across income categories (Appendix Table B4). Similar to the analysis of impacts, UMICs are overrepresented relative to their share of population, as these comprise 62.2% of the services studied. LoMICs and LICs are again underrepresented, with 30.8% and 7.0% of services, respectively. Moreover, UMICs are particularly over-represented in studies of cooling, transportation, and non-household income (e.g., 72.4% of all papers on cooling are in UMICs, compared with 25.3% in LoMICs and 2.3% in LICs). LICs and LMICs are relatively well represented in studies of cooking, lighting, and household-based income generation. These distributions may arise from a perception that cooling and transportation services are part of a minimum standard of living in relatively wealthier countries, but not in relatively poorer countries.[16]

4.4. Heterogeneity of impacts by technology

One might hypothesize that the number of impact studies and their findings (positive or negative, significant/non-significant) varies by

[16] In principle climatic differences could explain the distribution of papers on cooling services, but in practice many LICs are in the tropics, where cooling services would likely be in high demand.

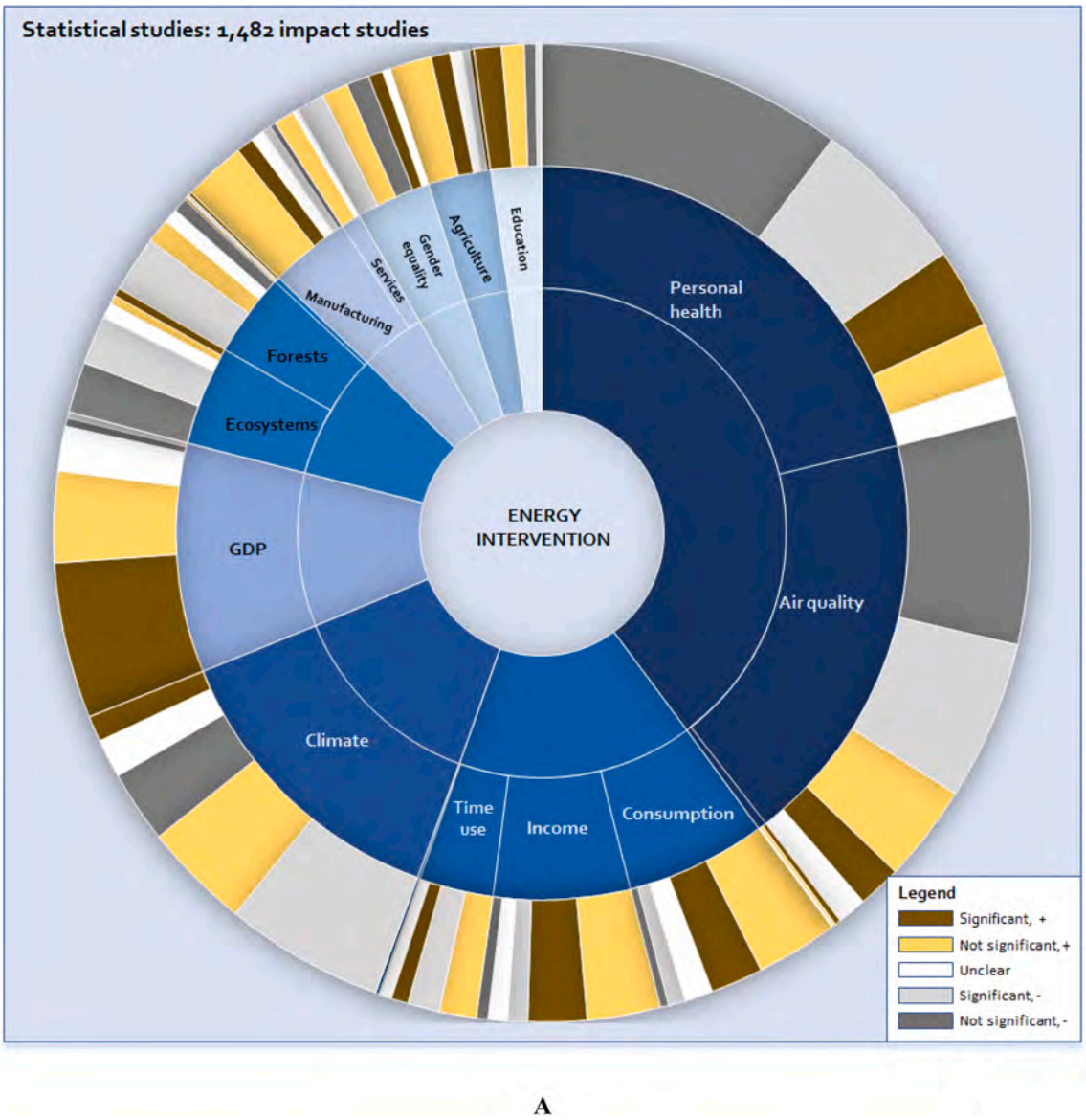


Fig. 4. Mapping of major impact categories of energy studies to the main SDGs that are linked to energy, for A) all statistical/econometric studies; and B) non-observational econometric studies only. The differentiated blue hues starting from the innermost circle correspond to the mapping between different impact types shown in Table 3 and various SDGs; these are split into different outcome (dependent variable) indicators as labeled in the second outermost circle. The outermost circle shows the proportion of measured impacts, according to statistical significance and direction. Note that statistical significance is not always reported consistently. [See appendix for results from non-statistical studies, for which statistical significance is not relevant.]. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

technology. For example, off-grid solar would be unlikely to change cooking practices and thus have small effects on household air pollution (via displacement of polluting lighting fuels), but might reduce fuel expenditures (for kerosene) considerably. Or, traditional stoves might damage air quality in a way that improved technology would not.

This idea is investigated by parsing the results shown in Fig. 4A by technology (relevant supporting figures appear in the supplementary Appendix to this article), first considering cooking technologies. For traditional cookstove studies (n = 698) that consider impacts, the evidence for most categories is overwhelmingly negative. These negative impacts map most strongly to health (air quality and personal health), climate, forest and ecosystem quality, and gender empowerment. The one exception is for poverty indicators: while time allocation evidence mostly indicates increased burden, likely reflecting the time burden of fuel collection, evidence for consumption and overall income is slightly more positive than negative in these studies, perhaps because traditional technologies and fuels are not purchased. A negative effect on the latter two indicators would thus depend on whether the time burden of fuel collection inhibits income generation (which is not well established). On the other hand, the evidence for benefits from improved stoves (n = 395) is mixed. Acknowledging that this category includes technologies that are themselves heterogeneous (ranging from improved biomass to gas stoves), there are comparable numbers of studies finding improvements and no improvements in terms of air quality, climate emissions, personal health, and forest and ecosystem quality. Evidence for poverty reduction is slightly more positive than negative, especially for consumption and expenditure, but this may actually reflect greater spending on fuel. A smaller number of studies have found evidence for improvements for firms (perhaps from local production of stoves), and agriculture and gender empowerment (perhaps due to time savings being used for

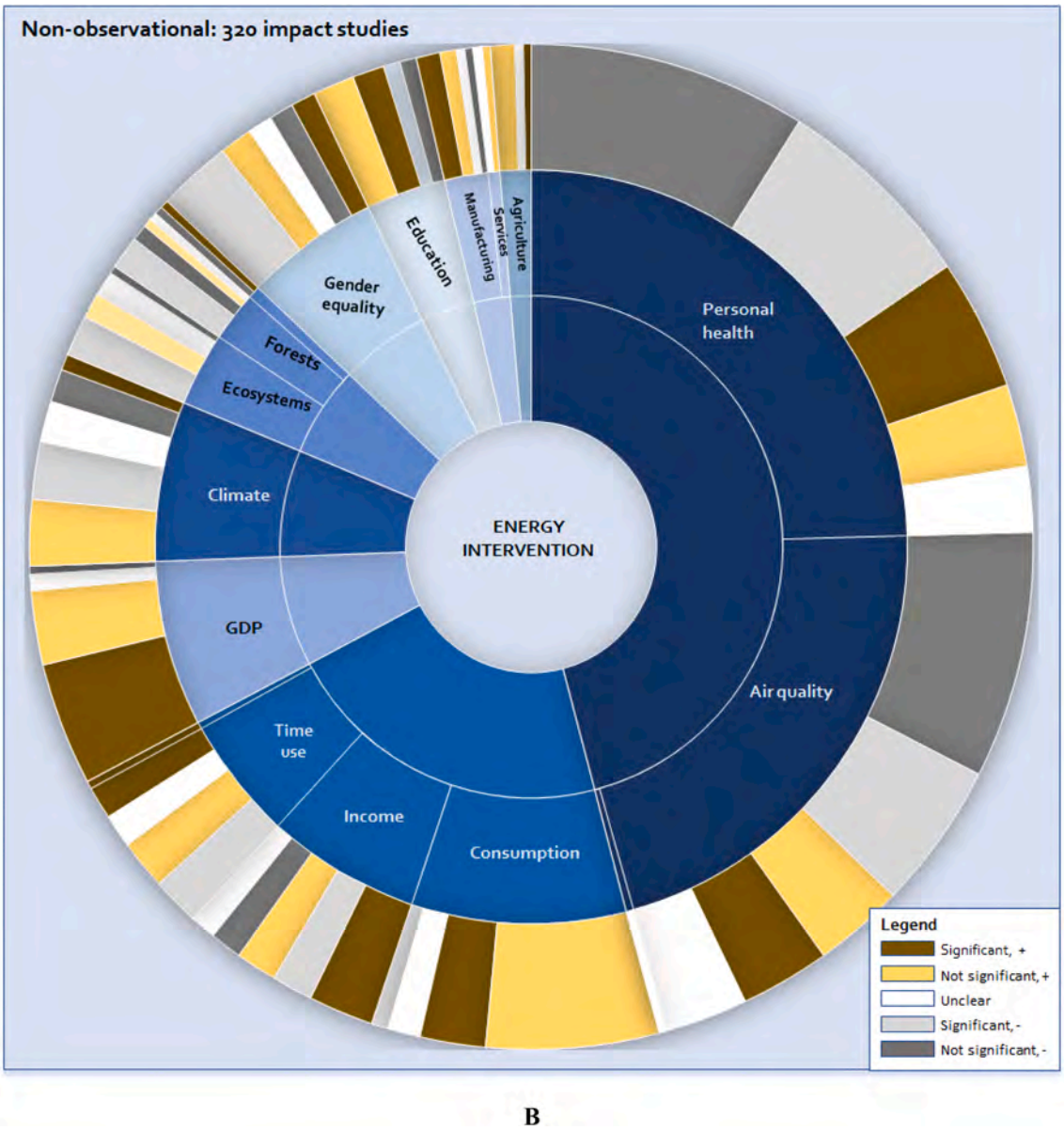


Fig. 4. (*continued*).

agriculture, and especially benefitting women, including through stove marketing [80]).

Turning to electricity, we begin with grid-based electricity studies (n = 598), and then proceed to various renewables including solar (n = 222), hydro (n = 165), biogas (n = 100), and wind (n = 57). Sample sizes of impact studies in the latter sub-categories become small, highlighting an important evidence gap. Consistent with the idea that grid electricity more often comes from fossil fuel-based generation, evidence in the environmental and health impact domains is mostly negative, although impacts of grid electricity on personal health are more positive. The latter result may stem from impact mechanisms that improve health via changes in income and quality of life. In line with this idea, impacts on consumption, household income, time allocation, education, gender empowerment, firm productivity and income, public services, and national GDP are predominantly positive. Still, there are almost equal numbers of statistically significant positive impacts and non-statistically significant positive impacts for these various indicators, pointing to some ambiguity and potential heterogeneity in the strength of these positive relationships. This body of evidence appears consistent with the well-known global sustainable energy challenge, which requires balancing of development and environmental concerns.

The evidence for the various renewables is substantially different and leads to a number of important observations. First, across renewables, impacts are mostly positive for the whole set of indicators, but remarkably few studies identify *statistically significant* positive impacts. Second, the impacts of solar appear universally positive, but unlike grid electricity, there are very few studies linking solar energy to national income and to firm income and productivity, air quality and health. This stands in contrast to a large modeling literature that makes claims about such relationships, and especially highlights tradeoffs between firm costs and environmental benefits [81,82]. Third, wind and biogas appear similarly positive, but studies of their impacts overwhelmingly consider environmental impacts (nearly 75% of impacts tracked relate to climate, air quality, and ecosystems effects). Neither of these latter two technologies have been strongly linked to economic growth in LMICs. Fourth, like grid-based electricity, hydropower presents important tradeoffs, mostly appearing to improve air quality, the climate, firms, household consumption, and national income; while harming ecosystems and forests; and having mixed impacts on agriculture, household income, and health.

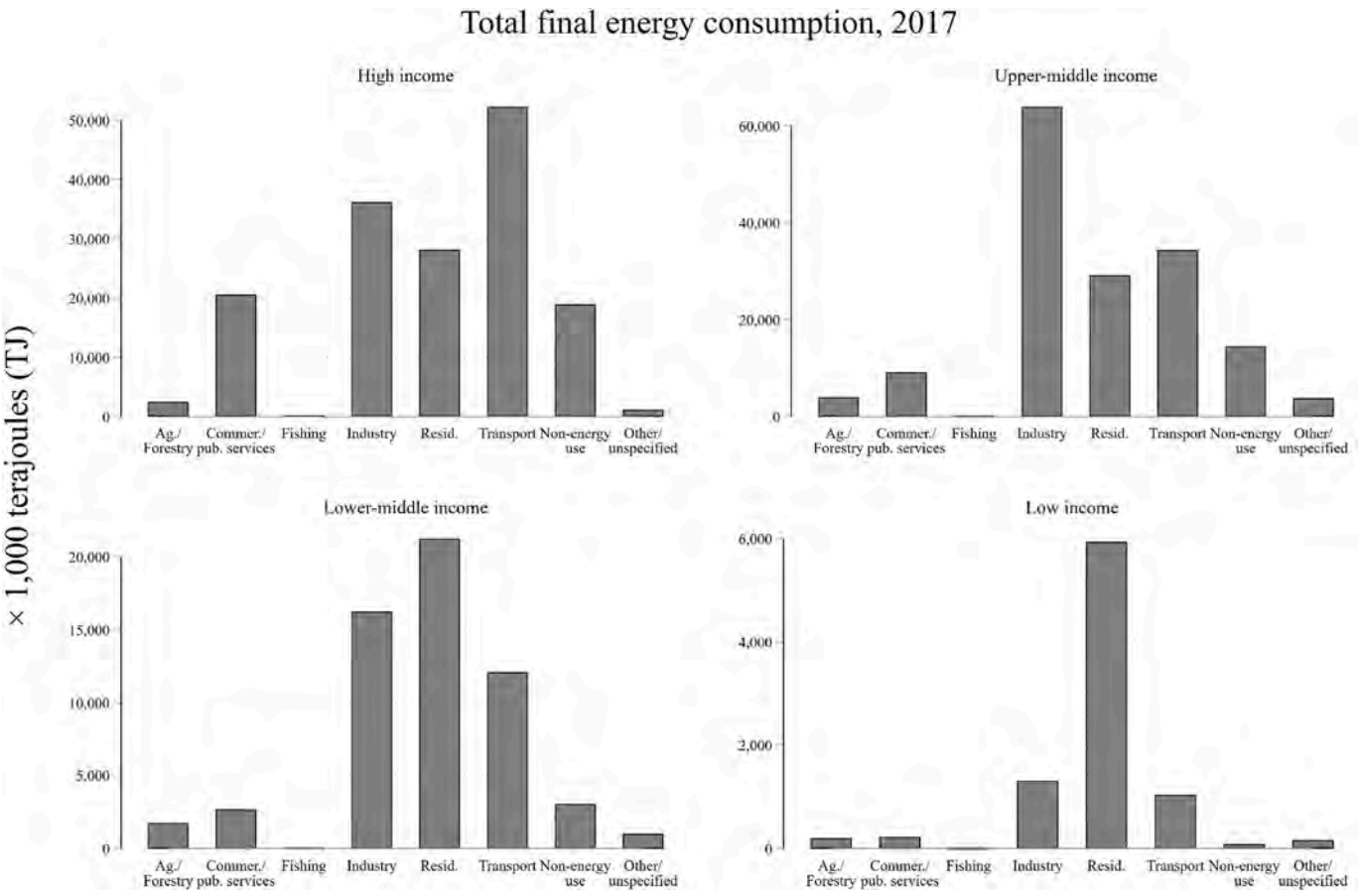


Fig. 5. Total final energy consumption for 2017 across different country income groups [Authors' analysis, using data from the International Energy Agency].

4.5. *Consistency of impacts across regions*

Another important source of heterogeneity in—and bias in potential extrapolation of study results on (see e.g., Hamburger et al. [83])—the impacts of energy access might arise from regional differences, due to variation in settlement patterns and density, general economic conditions, institutions, and/or appropriateness of different energy technology. This section explores several questions related to such regional differences, organized according to the World Bank geographies used in our coding scheme. These correlate somewhat with income levels, of course, and thus relate to the related prior discussion in Section 4.3 (countries in Sub-Saharan Africa (SSA) and South Asia (SA) tend to be in the LIC and LoMIC categories, for example, while those in East Asia and the Pacific (EAP) and Latin America and the Caribbean (LAC) skew towards the LoMIC and UMIC categories). The focus is on a limited set of outcomes for which there is sufficient econometric research to make cross-regional comparisons; all accompanying figures displaying this heterogeneity are included in supplementary Appendix B.

Regarding the regional distribution of impacts of traditional and improved cookstoves, a first observation is that studies of impacts on health are skewed towards SA, relative to air quality, where relatively more evidence comes from EAP (Figure B7 Panels A–D). This perhaps reflects the higher burden of disease due to poor air quality in the former region. Second, while traditional stoves are almost universally negative in terms of impacts on air quality and health, there is substantial regional heterogeneity in the impacts of improved stoves. Specifically, the impacts of improved cookstoves on health are much less positive in SA and SSA, relative to EAP and LAC region. This may reflect a tendency to promote more rudimentary improved technologies (so-called "transitional" options) that are less likely to deliver health benefits, in LICs [60,84,85], relative to middle- and even high-income countries [61, 86–89]. Finally, the evidence concerning the impact of cooking technology on gender equity, a commonly discussed issue in the literature, is extremely thin, with few statistically significant impacts identified, except with respect to negative effects of traditional technology in SA (Figure B7 Panels E–F). There is almost no evidence related to the impacts of improved stoves on gender equity, even in SA.

Turning to regional heterogeneity in the impacts of grid electricity, evidence related to national income—primarily from cross-country comparisons—is positive across regions, and many such results are statistically significant (Figure B8 Panel A). Findings in EAP are only slightly less positive than for other regions. Micro-level impacts are less consistently positive, however. For firm income, there have been few statistically significant and positive results from SSA and LAC, and results are also inconsistent in SA (relative to EAP, Europe and Central Asia [ECA], and the Middle East and North Africa [MENA]) (Panel B). Meanwhile, the impacts of grid access on household productivity and income indicators are also less consistently positive in SSA and SA (Panel C). Third, there is relatively little evidence of impacts on education, but these impacts are generally positive except in SSA (Panel D). Overall, a range of impacts appear less consistently positive in SSA, and to a somewhat lesser extent SA, compared to other regions. Finally, the impacts of grid electricity on the environment (both climate and air quality) have been studied extensively in EAP (in contrast to the relative cross-regional balance for other grid impacts), where they are more negative than positive. Evidence elsewhere is thin, and more mixed (Figure B9 Panels A–B). This may reflect differences in the timing of grid expansion and the fact that EAP has more mature grids that more readily demonstrate a tradeoff between development and environmental degradation, due to their ability to support higher energy consumption.

Regarding the impact of renewables, which are grouped together for only a few indicators due to the small number of such studies

(Figure B10 Panels A–C), four main observations emerge. First, the evidence is very thin overall. Second, the evidence in support of impacts of these technologies on productivity and income mostly includes non-significant results, with estimates that are slightly more positive than negative, except for ecosystems and forest quality. Third, the latter negative and statistically significant impacts mostly arise from studies of hydropower, and are concentrated in EAP and LAC. Finally, on climate, most impacts are positive, as expected, but surprisingly few results are statistically significant. This disaggregation confirms that there is very little documented evidence that renewable and off-grid energy technologies deliver positive impacts.

4.6. Does methodological difference explain differences in outcomes?

A potential concern with a broad-spanning review like this one could be that it weights all evidence equally without consideration for the quality of the studies or methods. As noted previously, the review did not include quality assessments of articles. It is therefore useful to consider briefly evidence separated according to the rigor of impact evaluation design—specifically that relying on quasi-experimental or experimental evaluation designs.[17] The sample size of such impact studies is relatively small (n = 320), making analysis by technology difficult, so this discussion is limited to qualitative commentary on consistency with the overall results presented above.

A first question to answer is: Is the distribution of impacts measured in such rigorous IE studies similar to that in the larger set of quantitative empirical papers? In comparing the size and position of the wedges in Fig. 4B to those in Fig. 4A, there are a few differences. Perhaps most striking is the increased proportion of measures of personal health and air quality as a fraction of all measures in these more sophisticated IE studies. About 90% of these impact measures come from studies related to traditional or improved cookstoves. A second major observation on the distribution of impact measures is that climate and forest or ecosystem estimates are uncommon, while impacts on gender empowerment and education are somewhat better represented in such studies. In general, and unsurprisingly, rigorous evaluation methods are more frequently applied to problems for which it is easier to construct such analyses, e.g., the behavior of small units such as households or individuals, rather than larger ones (e.g. firms, geographic areas, or even countries). Finally, it is notable that the percentage of total impact measures included in Fig. 4 for renewables (solar, hydro, biogas and wind) drops from 14% among statistical impact studies to 10% in the non-observational sample, compared to 26% in the full sample of quantitative impact studies. This highlights the relative dearth of rigorous empirical evidence related to renewables, compared to model-based analyses.

The second question is whether the direction of the impact measures is consistent across the full set of quantitative papers, and in the econometric and quasi-experimental/experimental sets. Somewhat surprisingly, there is only limited evidence of such inconsistency. For example, the relative proportion of negative and positive impact estimates for health and air quality is similar in the rigorous IEs compared to the full empirical set. The relative proportion of negative and positive results for most other impact categories is also mostly similar. The only exception is in statistical and non-statistical studies of impacts on consumption, income and time savings (non-statistical study results are summarized in Appendix Figure B5). All of these are generally less positive in the statistical studies compared to the full set, though patterns in observational and more rigorous IEs are surprisingly consistent. The former difference may be due to bias (e.g., optimistic assumptions about behavior change) in the modeling studies that aim to assess such impacts, or may be due to lack of precision or power in measures of impacts in statistical studies [90,91].

[17] Of course, it is important to recognize that not all quasi-experimental and experimental studies are of high quality. While the research designs themselves may be more rigorous, such studies can still fall short on a number of other important dimensions, e.g., lack of sufficient statistical power, low generalizability, or a range of problems that compromise internal validity.

5. Discussion and needs for further research

Many of the results of this broad-spanning review of the impacts of energy access and technology correspond to themes and debates that are apparent in dicussions among researchers and practitioners, including those emerging from prior, more narrowly focused reviews. In particular, there is much evidence on the negative impacts of traditional cooking technology, but findings are less consistent about the positive impacts of improved cookstoves—on health, time savings and other aspects of individual and household well-being. Electricity access, meanwhile, in general appears strongly linked to increased income and productivity (at household, firm and national levels) and negative environmental consequences, but a closer look at this evidence reveals that it does not extend consistently to all regions, technologies and solutions. For example, only a small number of studies have considered the role that off-grid renewable technologies play in raising income or in mitigating environmental damage from conventional energy technology, despite many advocates' expectations and claims to the contrary [92], and most of these do not estimate statistically significant effects. In general, it seems that the appropriateness of these different technologies for providing the energy services that beneficiaries actually want has not received sufficient attention. In effect, one key advantage of applying an energy services framework is that it helps to clarify what should be expected from specific interventions (e.g., the fact that off-grid electricity generation solutions may not deliver productive uses).

A summary of the most significant concentrations of research and gaps emerging from our review helps to guide research that would minimize duplication and redundancy and better inform decision making related to energy access interventions in LMICs. Of course, filling research gaps is only one of several necessary steps for increasing uptake of social science energy research [93]. The summary highlights specific energy services, impact domains, technologies, and regions, as appropriate:

1. Cooking services: Given the prevalence of solid fuel and traditional stove use for cooking in LMICs, this service deserves to be, and is, extremely well covered in the existing literature. Indeed, cooking is the energy service that appears most often in the reviewed papers. Unfortunately, many such studies provide only marginal value relative to implementers' needs for evidence, adding to a body of evidence that is already robust (e.g., showing that traditional stove use harm air quality and health, or documenting household-level barriers to adoption of improved stoves). What implementers need are studies that would more effectively help overcome serious supply chain, information, and behavioral obstacles that inhibit improved stove use and impacts, which remain decidedly mixed in the literature. Besides policies, the importance of complementary conditions (robust supply chains, market connectivity, access to financing) warrant attention, given the substantial variation in outcomes across regions. Finally, questions of affordability and the role of subsidies are especially important for determining impacts among the ultra-poor who rely most on traditional stoves.
2. Productive uses and increased incomes: As the review shows, a large body of research undergirds the finding of strong correlation between electricity access, firm and household productivity, and higher income. Such findings are not universal, however, and several prominent articles from various settings provide more rigorous evidence for [94], and doubts about [95–97], the causal relationship between energy access and a range of development outcomes. These divergent outcomes suggest that contextual factors and complementary economic conditions may play an important role in

mediating productive use [16,98]. They may also explain the regional heterogeneity that is apparent in studies of the impacts of electrification, and yet, the number of impact studies related to firm productivity and broader income impacts is small, especially in LICs.

3. Off-grid renewables, especially solar: There is tremendous buzz in the practitioner community about the potential of off-grid solar for reaching customers that are expected to remain disconnected from conventional energy solutions for some time. Installed solar capacity is rising quickly across LMICs, but it remains unclear that off-grid solar can sustainably and affordably deliver the services that people most want, such as refrigeration and productive uses, and the impacts that the energy sector expects, such as increased incomes. The review reveals that evidence supporting the benefits of renewables is limited and mostly inconclusive from a statistical perspective. There are also concerns about the quality of non-branded solar products [99], while some argue that the quality of such products is not necessarily worse than that of branded products that are also more affordable [100]. This further highlights the problem of consumer demand for solar. More research is needed on whether innovative service delivery models and improvements in battery storage can be leveraged to reliably deliver energy services other than lighting, phone charging, and entertainment, and how those translate into impacts.
4. Country or region-specific gaps: While energy studies can be found that cover all regions with LMICs, some locations, especially in UMICs, have greater concentration than others. Competent studies carried out in specific countries in which no or very few studies exist should be seen as valuable even if they are less innovative in addressing other gaps described above. Locations that are underrepresented in our review include several populous countries (e.g., Indonesia, the Democratic Republic of Congo, Angola), several countries for which we did not find a single quantitative study (e.g., Central African Republic, Chad), as well as underrepresented regions (e.g., SSA, compared to SA and EAP). Firm-level and national level impacts are infrequently studied in LICs.

A general thread connecting each of these ideas is that there is substantial heterogeneity in the impacts of energy in LMICs. While this review uncovers this heterogeneity, it only begins to explore why impacts vary in the way that they do, and this remains a critical knowledge gap. Indeed, assessing with certainty why something works or does not work is more difficult than simply showing reduced form impacts. Still, researchers need to work harder to craft studies that speak to mechanism (i.e., "why") questions, or need to leverage datasets—such as that assembled in carrying out this review—to carry out systematic hypothesis testing using meta-analysis of studies carried out in different contexts. To the extent possible, this work should be complemented by detailed qualitative work that also documents and explores the role of differences in institutions, culture and other contextual features that moderate or confound impacts over space and time, as these aspects limit generalizability from one context to another [101]. Such analysis is beyond the scope of our review, but is a promising area for future research.

Related to this, it is important to note that an emphasis on context does not negate the fact that there are many valuable lessons to be learned from countries at different stages of energy transitions. For instance, China's relatively rapid adoption of improved cookstoves provides lessons for other countries where traditional stoves remain widely used [101]. In practice, the set of applicable studies may be constrained: among countries that have made successful energy transitions, detailed data from the transition period are only available for some (notwithstanding the "energy leapfrogging" studies discussed earlier [32,102]).

A second thread relates to the need to design and grow systems that connect researchers and policymakers around existing knowledge and implementation gaps. As noted earlier, for instance, there exists an abundance of research on the negative relationship between traditional cooking technologies and air quality. While the review provides a systematic, empirical basis with which to highlight this skewed distribution, this insight that research on energy poverty going forward must prioritize a variety of other policy-relevant questions is not new [41]. Many crucial sectors remain underfunded, understudied, or both—and new structures are needed to better coordinate research efforts, outline funding strategies, and drive policy engagement on key topics across institutional and international boundaries, all while ensuring that experts and stakeholders from LMICs, where the burden of energy poverty is the heaviest, remain central contributors to the ongoing dialogue. The shapes these initiatives must take—and how they must tackle financing, logistical, and political economy challenges that inevitably emerge—is beyond the scope of this review. That they are needed to fully understand the scope of the energy poverty challenge and scale up effective solutions successfully, however, has rarely been clearer.

6. Conclusion

The broad-spanning review summarized here covered quantitative literature on the impacts of energy interventions in LMIC contexts. It was organized to characterize the coverage of existing scholarship along energy services, technologies, and impacts dimensions, and to map its findings to advancement towards achievement of nine connected Sustainable Development Goals. The energy-services/end-user framework for the review was found to capture the key sectors that are important from an energy consumption perspective as a function of countries' varying development positions, though the services to sectors mapping is not one to one. The approach also allowed identification of areas of both absence and concentration of research, and facilitated commentary on the consistency in results across methods, locations, and energy services. To summarize its findings: First, the geographic coverage of this literature is patchy; most populous countries are well represented, but there is a dearth of studies in lower-income countries in sub-Saharan Africa, where the burden of energy poverty is the heaviest. Second, energy transitions often reduce air quality, harm health, and damage the climate and environment, due to continued reliance on fossil or other polluting fuels, as well as ecosystem tradeoffs (e.g., from large hydropower dams). Third, while some technologies, and especially solar, have consistently more positive impacts, the empirical literature on their impacts remains very thin and limited (as it does for other renewables such as wind, micro-hydro, and biogas). This reflects the small share of solar energy in overall generation, but not the increase in attention and transformative potential expected of it by the global community. Fourth, scholars have been studying cooking services zealously, but mostly as they relate to air quality and health, rather than other impacts, despite the multi-faceted nature of the changes that cooking transitions entail; in addition, progress in achieving clean cooking targets is seriously lagging. Fifth, research on poverty reduction and income is more evenly spread across energy services, though the few studies on income, productivity, and GDP principally examine industrial energy use. And finally, too little attention has been devoted to understanding how the impacts of different energy transitions affect gender equity; public service quality such as health care and schooling; agriculture and service sectors (relative to manufacturing and industry); and forests and ecosystems (relative to air quality and climate forcing). These imbalances in the state of knowledge on energy intervention impacts impede policymakers' ability to act on messages about potential solutions, and lead to potential conflicts with other SDGs.

Data availability

The full dataset generated by this coding process is available via the Open Science Framework (OSF) digital repository at the following link: https://osf.io/3pa6g/.

CRediT authorship contribution statement

Marc Jeuland: Conceptualization, Methodology, Formal analysis, Writing - original draft, Supervision. **T. Robert Fetter:** Formal analysis, Writing - original draft. **Yating Li:** Formal analysis, Visualization. **Subhrendu K. Pattanayak:** Conceptualization, Methodology, Writing - review & editing, Supervision, Funding acquisition. **Faraz Usmani:** Conceptualization, Methodology, Validation, Formal analysis, Visualization, Writing - original draft, Project administration. **Randall A. Bluffstone:** Conceptualization. **Carlos Chávez:** Conceptualization. **Hannah Girardeau:** Investigation, Visualization. **Sied Hassen:** Conceptualization. **Pamela Jagger:** Conceptualization. **Mónica M. Jaime:** Conceptualization. **Mary Karumba:** Conceptualization. **Gunnar Köhlin:** Conceptualization. **Luciane Lenz:** Investigation, Visualization. **Erin L. Litzow:** Investigation, Visualization. **Lauren Masatsugu:** Conceptualization. **Maria Angelica Naranjo:** Conceptualization. **Jörg Peters:** Conceptualization. **Ping Qin:** Conceptualization. **Remidius D. Ruhinduka:** Conceptualization. **Montserrat Serrano-Medrano:** Conceptualization. **Maximiliane Sievert:** Conceptualization. **Erin O. Sills:** Conceptualization. **Michael Toman:** Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2020.110406.

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