Climate implications of electrification projects in the developing world: a systematic review

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Abstract

Energy is crucial to household health and consumption needs, and for enabling productive uses that enhance development. Yet, as of May 2020, 789 million people worldwide lacked access to electricity, far more had only low quality access, and about 2.8 billion people still burned biomass for cooking. The goal of achieving universal access to electricity, as formulated in the United Nations' Sustainable Development Goal (SDG) 7, ‘Affordable and Clean Energy’, is a high-level acknowledgment of the importance that modern energy plays in development. SDG 7 also seeks to balance modern energy access with Climate Action (SDG 13). However, past energy transitions and intensifications of now industrialized economies have widely been based on environmentally-damaging fossil fuels. While globally there is progress towards universal electrification, the transition towards a more sustainable energy system is lagging. Further complicating matters, a critical question remains unanswered and frequently challenged: Whether less fossil fuel-intensive pathways to electrification, e.g. based more heavily on utility-scale renewables and decentralized off-grid solar solutions, offer a viable path to development.

1. Introduction

Stable, reliable, accessible, and safe energy is crucial for improving household health and satisfying consumption needs, and for enabling the productive uses that enhance labor outcomes and income generation. Yet, as of May 2020, 789 million people worldwide lacked access to electricity, far more had only low quality access, and about 2.8 billion people still burned biomass for cooking. The goal of achieving universal access to electricity, as formulated in the United Nations' Sustainable Development Goal (SDG) 7, ‘Affordable and Clean Energy’, is a high-level acknowledgment of the importance that modern energy plays in development. SDG 7 also seeks to balance modern energy access with Climate Action (SDG 13). However, past energy transitions and intensifications of now industrialized economies have widely been based on environmentally-damaging fossil fuels. While globally there is progress towards universal electrification, the transition towards a more sustainable energy system is lagging. Further complicating matters, a critical question remains unanswered and frequently challenged: Whether less fossil fuel-intensive pathways to electrification, e.g. based more heavily on utility-scale renewables and decentralized off-grid solar solutions, offer a viable path to development.

While energy consumption and development strongly correlate, it remains difficult on a global scale to decarbonize electrification, and more generally, electricity supply. The past two decades have shown a tremendous (250%) growth of electricity demand in the Global South; the supply response to this has, by-and-large, been to expand fossil-fuel based electricity generation. A Renaissance of
emissions intensive coal has been observed, mostly driven by massive investments in China, India and other low- and middle-income countries (LMICs) [10, 11]. Though this trend is slowly coming to an end [12], additional lock-in of fossil generation capacity in the upcoming years will continue to be socially costly [13]. Moreover, modeling results indicate the possibility of technologically and economically viable renewable electricity pathways [14], but prior experiences offer only limited relevant empirical evidence that electrification can be entirely based on low carbon solutions and renewable energy in particular [15–17]. After all, though many electricity systems began as highly decentralized in a number of high income countries [18], nearly all such countries ultimately came to rely on grid extension supported by fossil fuel-based generation (for a recent analysis of the US experience, see Lewis and Severnini [19]).

Theoretically, investment in ‘off-grid’ and largely renewable solutions appears to be a win-win that is both climate sensitive and meets energy needs [20]. But some note that such solutions may not be conducive to economic growth, because electricity consumption from typical off-grid applications tends to be very low [15]. Even grid-based electrification may not spur development when consumers’ use little energy [21], or if the complementary conditions that foster increased demand for energy are not present [22, 23]. In the face of mixed outcomes, political pressure to deviate from an ‘on-grid’ pathway, towards off-grid technology that risks locking in low levels of electricity consumption, might remain low in the near term. This may result in more investment in centralized, fossil fuel-based energy production, with adverse long term implications for the global climate.

Given this fundamental challenge, the central objective of this review is to better characterize quantitative evidence from field-based (in contrast to predictive modeling) studies on the relationship between on- and off-grid electrification strategies, on the one hand, and climate and development or energy services-related outcomes, on the other. While prior studies have separately discussed the impacts of electrification on productivity, economic well-being, and development [2, 24–27], or climate outcomes [28–32], comparative synthesis of these threads is missing in the literature [27]. We envisage to show if specific types of electrification (on-grid or off-grid) are associated with different climate and societal impacts, focusing on household electricity and related energy services as proxies for well-being, as well as more scarce evidence on productive use and development. More specifically, we aim to investigate the determinants of heterogeneity in those outcomes across contexts, technologies used, study methods, and time. Here we refer to energy services as the basic end uses for which electricity may be necessary (e.g. lighting, cooking, heating, consumption of entertainment, transportation, communications, and/or productive use of energy especially for generating income) [27]. We apply this framing because it is the provision of energy services that ultimately influences the longer-term development potential of different electricity generation technologies. We hypothesize that differences in electrification strategies may produce a different quality of power supply, as defined by the multi-tier framework (MTF) construct of the World Bank [33], enabling different energy services, and inducing different emissions and development outcomes. Note that—despite the fact that it is an interesting research question—our research framework does not allow identification of the reasons why countries in specific contexts invest (or do not invest) in grid-based electrification, nor can we say anything on the question of why people use or do not use electricity even if is available.

Beyond analyzing current scientific evidence, we aim to offer insights on the degree to which potentially conflicting development and emissions objectives can be balanced. We especially highlight the key issues that must be addressed if past patterns of fossil fuel-intensive and environmentally-damaging energy sector development are to be avoided. Our contribution, relative to the broader literature, is firstly, as noted above, to focus on the climate and development nexus of energy transitions, rather than one or the other of these in isolation. Second, most of these prior reviews did not rely on a systematic or replicable search strategies but rather on ad-hoc and often subjective search criteria and strategies. In contrast, we implement a transparent search procedure to allow for updating of our results given that we expect the literature on this crucial topic to expand greatly in the near future. Below, we describe our approach in greater detail, then present the results of the review and analysis, and finally close with discussion and interpretation of these results.

2. Methods

2.1. Scope of the review

This section specifies the research fields covered in our systematic review, and defines key terms or concepts. The review aims to capture literature that addresses the development and climate implications of electrification efforts in developing countries, and thus draws from economics, engineering, and natural science literatures. Importantly, it only includes papers that obtain empirical data on the climate impacts of electrification, (field-based) measurement of energy consumption, or proxies for it (e.g. capacity or quantified use of energy services). In choosing to compile such empirical literature on climate and development responses to electrification, we limit our investigation to real-world ex-post evidence, in contrast to more theoretical approaches that may only partially align with observable patterns.
In speaking about electrification, we first appeal to a binary construct that allows for any type of electricity use (from pico-lighting to full connections to grid power). We then extend this concept of electricity access, according to its multiple dimensions of capacity, availability, reliability, quality, affordability, legality, and health and safety, following rough application of the MTF concept [33]. We additionally investigate how the energy services provided or utilized (using the typology presented in Jeuland et al [27]), vary across generation technologies (fossil fuels, hydropower, wind, solar, geothermal, other) and grid type (fully grid, mini-grid, user-level off-grid, and hybrid grid + off-grid). To characterize the climate implications in each study, we derive estimates of the carbon intensity based on the combination of information on grid type, generation technology (e.g. for off-grid diesel), and/or grid emissions factors, reported by the IEA (in 2017).

2.2. Identification of articles
Our strategy for capturing articles on this nexus was developed based on the following considerations:

(a) The need for a tailored search string combining terms in three categories: (a) country or region-specific identifiers to capture developing regions; (b) terms for electrification or power generation technologies, including grid and off-grid specifiers; and (c) emissions-relevant terms, related to electricity consumption or proxies for it. We did not include development and energy service related terms because we determined, based on initial piloting, that these further restrictions were unnecessary or even prohibitive. The final search string, included in the appendix to this article, emerged from an iterative process that added and excluded key words in an attempt to balance the scope and relevance of identified papers.

(b) Implementation of the search in publicly-accessible interdisciplinary article databases of peer-reviewed literature, namely Web of Science and Scopus. We searched based on the topic field, which considers title, abstract and author keywords only, and limited the scope to English-language articles published after 1992 (and extending through 2018).

The total number of articles captured in this way was a list of 576 peer-reviewed papers; we then applied our study inclusion criteria. Specifically, each included study had to (a) cover an electrification experience in one or more LMICs; (b) be an empirical study that included data from real-world interventions and projects; (c) allow for categorization into grid, off-grid, or hybrid electrification options; and (d) provide information on emissions outcomes, or proxies from which emissions could be inferred, such as electricity consumption levels and technology identifiers. Articles did not have to make an explicit link between grid and off-grid technology and energy consumption, but did need to report on these to allow further analysis and inference based on their reported data. Furthermore, articles did not need to directly analyze emissions and development outcomes to be included in the review, although our analyses of them consider this nexus.

Finally, we were cognizant that we would miss relevant grey literature as well as relevant peer-reviewed articles given the search string and idiosyncrasies of the article databases in which that search was implemented. Thus, we reviewed abstracts and, when necessary, full texts of all references from the retained articles (following application of inclusion criteria), as well as documents citing those retained articles (using Google scholar).

The first round of screening—based solely on titles and abstracts for the original 576 articles—with the study inclusion criteria yielded a list of 135 potentially relevant articles (figure 1). A second round of screening based on a full text review further reduced this list to 32 articles. In most cases, this additional full-text screening eliminated articles that did not rely on real empirical data or that did not allow inference about the emissions involved with the interventions/technologies. The second stage identification of articles based on the abstracts and titles of forward and backward citations to these 32 retained papers yielded an additional 68 potentially relevant articles. Only 4 of these 68 met the study inclusion criteria. Table 1 provides a descriptive classification of the key research foci covered in the final sample of 36 papers, as well as the countries represented in the papers under each theme.

2.3. Coding of retained articles
After screening, articles were coded according to a system developed and discussed by all co-authors involved in the systematic review, and submitted to a pre-review of the full research protocol (see appendix in supplementary material https://stacks.iop.org/ERL/15/103010/mmedia for the full protocol that was revised based on comments.
| Research theme or focus                                           | # of papers | Countries                                                                 |
|------------------------------------------------------------------|-------------|---------------------------------------------------------------------------|
| Determinants of electrification                                  | 15          | India (7), Rwanda (2), Kenya, Bangladesh, Brazil, Mozambique, Namibia, SSA |
| Determinants of electricity consumption or services obtained     | 13          | India (5), Kenya (2), Brazil (2), China (2), South Africa, SSA            |
| Energy poverty concepts and dynamics                             | 10          | India (6), Bangladesh, Brazil, China, Mozambique                          |
| Appropriate technology, based on cost, consumption levels or preferences | 10          | India (4), Kenya (2), Namibia, Tanzania, SSA (2)                          |
| Electricity system design and planning                           | 10          | India (5), Peru, Kenya, Namibia, Tanzania, SSA                           |
| Impacts of electrification: Development (income and productive use) | 9           | India (2), Rwanda (2), Brazil, Kenya, Namibia, SSA, ECOWAS                |
| Targeting of real-world electrification interventions            | 8           | India (2), Brazil, Columbia, Kenya, Rwanda, South Africa, ECOWAS          |
| Impacts of electrification: Human capital (health and education) | 7           | India (2), Rwanda (2), Namibia, ECOWAS, SSA                              |
| Maintenance and long-term sustainability                        | 5           | Columbia, Kenya, India, Namibia, Peru                                    |
| Impacts of electrification: Time and expenditures                | 5           | Rwanda (2), India, Namibia, SSA                                           |
| Estimation of emissions generated by energy consumption          | 2           | China, India                                                              |
| Business models and scale-up                                     | 1           | India                                                                     |
| Illegal electricity use                                         | 1           | Brazil                                                                    |

Notes: A single paper may cover more than one of these foci, but all papers have at least one of those listed above.
obtained by two anonymous referees). This coding scheme covers the following five aspects:

- General article information.
- Variables related to electrification, specifically: (a) grid/off-grid characterization; (b) end uses for energy provided (production, home consumption, public use, general use); (c) energy services provided, based on the characterization in Jeuland et al [27]; and (d) generation technology.
- Empirical methods, specifically: (a) observational, quasi-experimental, experimental, review, or other;\(^8\) (b) inclusion and type of counterfactual; (c) unit of analysis; (d) data type; and (e) sample size.
- Energy use or emissions implications, specifically: (a) empirical measures of consumption or proxies for consumption, including units; (b) modeled estimates of consumption; (c) empirical or model estimates of climate-forcing emissions, as well as details related to those estimates (input variables used, forcing agents included); and
- Development implications, specifically: (a) indicators and units; (b) whether based on statistical or econometric analyses; (c) magnitude of impact; (d) significance of impact; and (e) control variables included and assessment of robustness of estimate of impact.

With this scheme, we aimed to extract all relevant and comparable information to obtain a comprehensive overview of the scopes, methodologies, energy (or emission) implications and development impacts of included articles to adequately characterize empirical and quantitative evidence on the

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\(^8\) We use the ‘quasi-experimental’ term for studies that create rigorous treatment-control comparisons via methods other than randomization, e.g. matching, instrumental variables, difference-in-differences, or that exploit natural experiments.
relationship between on- and off-grid electrification strategies and climate and development or energy services-related outcomes. The coding process was completed by two researchers. All 135 articles that were initially screened based on title and abstract were subjected to a full text review by both researchers, and the relevant subset double coded to assess consistency. In the few cases with inconsistencies across coders, the disagreements were discussed and resolved through consultation among the study authors.

Overall, we find a high diversity of approaches and inconsistencies across the included studies, as well as the relatively small number of articles in the literature that met our inclusion criteria. Indeed, the themes shown in table 1, which for the most part are based on the original authors’ own descriptions of their contributions, are quite heterogeneous, with the largest concentration of papers having to do with the determinants of electrification, electricity consumption behavior, or energy poverty; and electricity system design and planning or appropriate technology. Other papers are predominantly focused on the impacts of electrification or sustainability issues, and very few (only 2) discuss emissions as a central aspect of their research. Our analysis therefore focuses on a descriptive mapping of themes and topics which is supported by descriptive and comparative quantitative analyses. More in-depth analysis techniques to answer our primary research questions, such as meta-analysis, were deemed to not be appropriate due to an insufficient number of studies with comparable research approaches.

2.4. Limitations
Building on this last point, we note here the main limitations that we judge to affect this review. First, we are highly constrained by the limited available literature, and the fact that it does not perfectly address the nexus of electrification’s climate emissions and development implications. The limited literature means that many LMICs and regions are scarcely represented in the review, in particular West Africa, parts of Asia outside of South Asia, and many countries in Latin America. Larger, more populous LMIC countries tend to be better represented but Nigeria, the Democratic Republic of Congo, and Indonesia are notably absent. Countries further along the energy transition, such as lower middle-income countries, are better represented than less developed countries. This geographic bias may also be due to our limiting the review to English language literature, which favors Anglophone countries. Second, due to our desire to quantify emissions, we neglect qualitative literature, which may nonetheless carry many insights particularly regarding the development and well-being implications of electrification. Relatedly, again due to our desire to quantify emissions, the search prioritized identification of articles with real energy consumption estimates, but most development and even climate-relevant articles do not include such estimates, which can be difficult to obtain owing to lack of metering or detailed survey data on energy use patterns. Given these limitations (more inclusion of middle-income and metered situations), it is possible that our review over-estimates the level of consumption in many electrification experiences.

3. Results
To begin our quantitative synthesis of the papers, we describe its coverage in terms of geography, electrification characteristics, and methods variables as listed above. We then consider how the study measures or describes energy consumption, services and, when applicable, emissions and development outcomes.

3.1. Characterization of the retained papers
Considering first the geographical and temporal coverage in this literature, our first observation is that more than a third of the papers (14 of 36 papers) focus on the electrification experience of India (table 2). India is certainly an important country in that it is both very populous and has made great strides in extending electricity access to unconnected communities and households over the past two decades [34, 35]. It is also a leading location for adoption and experimentation with off-grid technologies and supporting business models [36]. What is striking about this relative concentration on India, considering the relatively small set in this literature overall, however, is the dearth of papers from other regions where electrification rates have also improved at different rates [37]. This is perhaps most true of Sub-Saharan Africa outside of East Africa, where we identified a sum total of four papers. Latin America and East and Southeast Asia are also poorly represented in this literature, but the experiences of those regions are less relevant to our review, since they are already nearing universal electricity access and most of their countries have only marginally relied on off-grid technologies. The depth of this literature is growing over time; two thirds of the papers are from after 2014 (figure 2).

Turning next to the relative balance of on-grid and off-grid papers, we observe that a slightly larger number focus on off-grid electrification approaches (25 papers, vs 20 papers for on-grid; some papers include both of these approaches), which is relatively surprising considering that grid-based electrification still supplies the majority of new connections in developing regions. This may reflect the relative novelty of off-grid technology and a greater perception of

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9 A precise application of the MTF concept is not fully possible since it requires much more data, on these various dimensions of electricity supply, than is typically reported in papers on electrification. Still, we are able to distinguish low (tier 1 and 2) and higher (tiers 3 to 5) levels of electricity access with a high degree of confidence, based on reported consumption levels and energy services used.
Table 2. Count of review papers by country, electrification technology, use of energy, and energy service.

| Country/Region | N | Grid | Off-grid | Household | Other | Production | Home Consumption | Lighting | Cooking | Heating | Phone | Enter-tainment | Solar | Wind | Hydro | Biogas | Fossil | Not specified |
|----------------|---|------|----------|-----------|-------|------------|------------------|----------|---------|---------|-------|----------------|-------|------|-------|--------|--------|---------------|
| Bangladesh     | 1 | 1    | 0        | 1         | 0     | 0          | 1                | 1        | 0       | 0       | 0     | 1              | 0     | 0    | 0     | 0      | 1      | 0             |
| Brazil         | 2 | 2    | 0        | 2         | 0     | 1          | 2                | 1        | 0       | 1       | 0     | 2              | 0     | 1    | 0     | 0      | 0      | 2             |
| China          | 3 | 3    | 0        | 2         | 0     | 0          | 2                | 2        | 2       | 1       | 1     | 2              | 1     | 0    | 1     | 0      | 1      | 2             |
| Colombia       | 1 | 0    | 0        | 1         | 0     | 0          | 0                | 0        | 0       | 1       | 0     | 0              | 0     | 2    | 0     | 0      | 1      | 0             |
| India          | 14| 6    | 12       | 10        | 4     | 2          | 12               | 11       | 3       | 0       | 7     | 5              | 8     | 0    | 1     | 1      | 2      | 6             |
| Kenya          | 3 | 1    | 4        | 1         | 0     | 2          | 3                | 3        | 1       | 0       | 1     | 3              | 2     | 0    | 0     | 0      | 1      | 0             |
| Mozambique     | 1 | 1    | 0        | 1         | 0     | 0          | 1                | 1        | 1       | 0       | 0     | 0              | 0     | 0    | 0     | 0      | 0      | 0             |
| Namibia        | 1 | 0    | 1        | 0         | 1     | 0          | 1                | 1        | 0       | 0       | 0     | 0              | 1     | 1    | 0     | 1      | 0      | 0             |
| Peru           | 1 | 0    | 2        | 0         | 1     | 1          | 1                | 1        | 0       | 1       | 1     | 0              | 1     | 0    | 1     | 0      | 0      | 0             |
| Rwanda         | 2 | 1    | 2        | 2         | 0     | 0          | 2                | 2        | 0       | 0       | 1     | 2              | 1     | 0    | 1     | 0      | 0      | 0             |
| South Africa   | 1 | 1    | 0        | 1         | 0     | 0          | 1                | 1        | 0       | 0       | 0     | 1              | 0     | 0    | 0     | 0      | 0      | 1             |
| Tanzania       | 1 | 0    | 1        | 0         | 0     | 0          | 1                | 1        | 0       | 0       | 1     | 1              | 1     | 0    | 0     | 0      | 0      | 0             |
| Region         | 0 | 0    | 0        | –         | –     | 0          | 0                | 0        | 0       | 0       | 0     | 0              | 0     | 0    | 0     | 0      | 0      | 0             |
| Africa         | 2 | 1    | 1        | 0         | 2     | 0          | 1                | 1        | 0       | 0       | 0     | 1              | 1     | 0    | 0     | 0      | 0      | 1             |
| ECOWAS         | 1 | 1    | 0        | 0         | 1     | 0          | 1                | 1        | 0       | 1       | 0     | 0              | 0     | 0    | 0     | 0      | 0      | 0             |
| Sub-Saharan Africa | 2 | 2    | 2        | 0         | 2     | 2          | 2                | 2        | 2       | 0       | 1     | 2              | 1     | 0    | 0     | 0      | 0      | 2             |
| Sum            | 36| 20   | 25       | 9         | 8     | 31         | 30               | 10       | 4       | 14      | 20    | 16             | 4     | 4    | 1     | 5      | 17     |               |
the need for research on the effectiveness of efforts to extend access using it. What is more surprising is the predominant focus on household users (relative to more intensive energy users such as businesses and industries), and on home consumption rather than production. Only 9 (25%) papers include a unit of analysis for energy consumption and use other than a household, and only 8 (22%) address production, whether home or otherwise. Furthermore, the most commonly identified energy services are consumption services: lighting (28 papers), followed by entertainment (16) and phone charging (10). These patterns partly reflect the fact that in the past off-grid electrification (for which there are more papers) infrequently allowed more intensive energy uses due to low installed capacity (table 2), and the fact that researchers writing papers on grid electrification have infrequently applied an energy services lens—perhaps because capacity is less constraining. Consistent with this idea, few papers speak to use of services that require more power—cooking, heating, or refrigeration. The tiers (1–2 vs 3–5) inferred from these data, disaggregated by grid and off-grid approaches, are shown in figure 3.

The generation technology covered in the papers also parallels these trends. Roughly half of the studies we reviewed were related to solar energy; these encompass most off-grid studies (a few papers consider diesel generation). Relatively few studies explicitly mentioned fossil fuel-based generation, and we therefore used a ‘non-specific’ generation category to account for studies that relied on the grid or were otherwise unclear about generation.

The included empirical studies nearly all use observational data and analysis (30 of 36 studies); the remaining use experimental (2 studies) or quasi-experimental (5 studies; note that one such study includes a mix of observational and quasi-experimental approaches) research designs. In accordance with these methods, relatively few studies explicitly claim to identify causal links between electrification and other outcomes; those claiming to do so primarily use experimental or quasi-experimental methods. Moreover, among the observational studies, roughly half include multivariable regression methods to analyze the primary relationships of interest, but the other half do not control for other factors or are mainly aimed at descriptions of electrification experiences supported by descriptive statistics and techno-economic modeling.

3.2. Emissions, electricity characteristics, and development implications of different electrification strategies

One explicit goal of our study is to investigate the nexus between climate implications and electrification. Hence, as discussed in the methods section, our systematic review only targets studies that allow estimation of emissions outcomes, or proxies from which emissions can be inferred based on electricity consumption levels and technology identifiers. Only four studies reported emissions information

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10In particular, we compared articles identified using the search string to a small group of articles that had been identified based on ad-hoc searches that were implemented during the pilot development of the tagging and coding scheme for the review. This piloting was done drawing from a randomly selected group of articles retained in a prior, much wider-spanning systematic review of 80 000 + articles addressing the impacts of energy transitions in low- and middle-income countries (22).
directly, and these reports were limited to CO$_2$. Since the remainder required estimation of emissions from consumption or generation capacity, we standardized this approach and applied it even for the four studies that directly reported emissions estimates.

More specifically, we calculated the emission intensity of on-grid and off-grid electricity consumption as well as of the investigated energy services in the respective study year and country covered by our sample. For grid-based electrification, we obtained the emissions intensity of the public grid by using data on grid-connected power plants from the IEA (2017). This assumes that national grids are mostly interconnected such that average emissions are relevant, and that the marginal generation for additional connections entails emissions that are similar to the average for the country. We also checked that our sample of countries did not include any that depend heavily (>5%) on electricity imports, which was the case for all but Mozambique (we excluded this study as a result).

For off-grid electrification, we assumed that emissions would be equal to zero for renewables (e.g. solar, micro-hydro), and used capacity and emissions estimates for non-renewables (e.g. diesel generators) taken from the IPCC emissions (IPCC 2006). We addressed data challenges that arise due to mixed electrification and inconsistent reporting conventions in our included studies by applying appropriate assumptions or estimations. Specifically, the main challenges in implementing this approach were insufficient details on the relative balance of renewable and non-renewable sources in cases with mixed electrification options, or inconsistencies in authors’ reported units or consumption proxies (e.g. reporting lighting hours per day versus kWh/day). When details reported in the studies were insufficient to obtain valid estimates of consumption (e.g. lighting hours were specified, but the most common type of light bulb in the setting was not), we filled in the median consumption value from the full set of other studies covering the same energy services as the one in question, and calculated emissions according to the logic previously described.

Based on this approach, we distinguish the tier implications according to the electrification strategy (on-grid or off-grid) (figure 3). As shown, off-grid approaches, dominated by solar technology, are more likely to provide low tier access relative to grid-based approaches. Though there are relatively few studies that cover on-grid and off-grid access together, the results from these studies suggest that hybrid models tend to more closely resemble off-grid in their implications for the level of electricity service. This is likely due to the types of communities and users (more remote and lower income) targeted by the interventions that are analyzed by the respective studies.

In addition, we map the tiers of consumption or energy services used, to emissions, as shown in figures 4 and 5. Since lighting, phone charging, and some basic entertainment services have been provided by off-grid or solar technology, the lower consumption bounds for each of these studies tend to come from such solutions, whereas mini-grids, diesel generation, or the grid are required for other higher energy consuming services. Heating, cooling and cooking services are almost never seen in combination with solar power, and are predominantly provided by grid electricity. Off-grid technology can
in some instances entail very high emissions that exceed those of typical grid systems, as in the case of diesel generators that provide higher tier access (figure 4). Considering the emissions implications of different energy services, we observe that lighting, phone charging, and basic entertainment in our sample have negligible climate effects—this combination of services is also easily provided by systems that rely on off-grid solar technology alone. Emissions are higher with the addition of cooking and other appliances, as well as heating. Yet low emissions situations with even these more demanding energy services are
also occasionally found—most typically with less carbon intensive electricity grids, or as minority uses from off-grid solar systems.\textsuperscript{11}

Our sample thus reflects well the basic intuition about the patterns of energy services associated with off-grid and renewable technologies in low income countries, that is, that these provide energy mainly for low capacity services, such as lighting, phone charging and entertainment, whereas energy-demanding tasks, at least at a large scale, have been more heavily dependent on the provision of grid power or emissions-intensive diesel. Still, the study sample also indicates a research bias towards small-scale solar installations, as opposed to mini-grids.

4. Discussion and conclusion

In this systematic review we aimed to understand the interlinkages between electrification strategies in LMICs, and their impacts on climate and development. The review provides a set of important insights and more importantly, reveals key gaps in our understanding of these relationships.

First, and in and of itself an interesting result, despite a large literature linking energy poverty and health-damages from household air pollution\cite{27, 38, 39}, we find very little literature that explicitly looks into the nexus of climate change emissions and electrification. What literature exists is also spotty in geographic representation, with a very evident gap in West Africa. The reasons for the lack of representation of different developing regions are undoubtedly complex; prior literature has noted the role of researcher or journal bias in influencing topics studied, for example, but likely other contributing factors include low data availability and research capacity, as well as methodological challenges facing infrastructure evaluations\cite{27, 40–42}. It thus seems that questions of energy access and sustainable energy (SDG 7) and climate change mitigation (SDG 13) are often discussed in different communities that work separately from one another, even though our sample contains especially more recent literature. Better understanding of this nexus, for example by exploring the role of renewables-based mini-grids in fostering development in rural areas, is an interesting and important topic for future research. This observation echoes several recent calls for more collaborative work by environmental and development-oriented scholars and practitioners\cite{43}.

Second, our analysis shows that providing households with electricity that goes beyond very basic needs (Tier 1 and 2) and services (lighting, phone charging, and entertainment) has mostly been realized via on-grid electrification. The link that we demonstrate between off-grid electrification and Tier 1 and 2 highlights the difficulties facing many of these investments, which encompass technical feasibility, affordability, and sustainability challenges\cite{44, 45}. Many of these same challenges also faced decentralized systems that were deployed in the early stages of electrification in today’s rich countries\cite{18}. The literature has identified various reasons—different capital cost and institutional or managerial structures of fossil and renewable energy technologies, positive spillovers induced by coal, high financing costs of renewables, and intermittency and vulnerability to outages—why developing countries are not investing in large-scale renewable generation\cite{46–52}. And though the challenges facing off-grid renewables are increasingly being resolved, the empirical link between grid extension, and Tier 3–5 energy services as well as energy-intensive development, will almost surely sustain perceptions of the attractiveness of on-grid solutions for some time. Additionally, vested interests of policy-makers in coal and personal interlinkages with incumbent industries exacerbate the difficulties facing emerging renewable energy industries\cite{53}.

Third, these realities of course have important implications for the climate effects of electrification efforts. As our calculations show, on-grid electrification is usually carbon intensive, while off-grid electrification via renewables is typically climate neutral. Exceptions can be found in countries with large hydropower potentials, such as various Latin American countries, or mountainous Nepal and Ethiopia\cite{54, 55}, and in the other direction, in the usage of off-grid diesel generators. Given the large number of people with no, or only low quality electricity access, questions about how to decarbonize electricity supply while overcoming fossil-fuel based technologies such as coal or natural gas thus become increasingly important. As a back of the envelope calculation based on our results, providing Tier 3–5 access to all 150 million households that still lack any access to electricity would—based on our full sample entail additional annual emissions of about 76 Mt of CO\textsubscript{2} (compared to 1.52 Mt off-grid and 19.2 on-grid for Tier 1 & 2). As most of these households lacking any electricity reside in Sub-Saharan Africa, this could increase total energy- and industry-related carbon emissions in the region by 30% (based on 2015 values). Perhaps more significant, though, would be the emissions impacts of raising the level of access for the billions of LMIC households who currently receive low (Tier 3 and below) levels of electricity service, unless significant breakthroughs in renewable generation and integration into the grid can be achieved soon.

As such, whether electrification makes a significant difference to global climate-related emissions very
much depends on the level of access and thus the extent of electrification. If considering only low service level (Tier 1–2) access for households, climate related emissions are irrelevant, as others have also noted [28]. This situation changes, however, if and when households acquire more energy-demanding appliances and technologies, supported by higher levels of service and thus emissions-intensive on-grid electricity supply. Another consideration is that our estimates are based on existing infrastructure, which in many LMICs (especially in Africa) relies heavily on generation from low-emitting hydropower. The average emissions intensity in our sample (362 g kWh$^{-1}$) ranges well below the most polluting grid-based technologies. Recent evidence of quickly electrifying LMICs, including in sub-Saharan Africa, in contrast indicates increasing investment in emissions intensive coal-fired or other fossil fuel-based generation [10]. A (hypothetical) electrification scenario similar to the coal-based trajectory of South Africa’s grid development (966 g kWh$^{-1}$) would roughly double emissions in these countries, increasing them by more than 200 Mt a year.

It is hence increasingly important to think of possibilities for accelerating a transition to less carbon intensive modes of provision of grid-based electricity. There is no fundamental reason why large-scale renewables cannot provide more advanced energy services in the future. For example, the higher financing requirements for renewables in LMICs could be supported by high income countries by de-risking investments, providing direct investment, or otherwise subsidizing renewable capacity [56]. Technical challenges such as intermittency will become increasingly manageable and economically feasible as battery costs continue to drop. Industrialized countries are increasingly demonstrating the feasibility of grid balancing, and these can support LMICs with knowledge transfer. The potential short term and local benefits, or opportunity costs, of building fossil capacity, could likewise be compensated. Carbon pricing schemes in high income countries could help generate the revenues required for such compensation, while simultaneously disincentivizing fossil fuel investment and setting a clear signal to the market.

While our review provides multiple insights, we find that overall the nexus of climate and electrification in the context of development remains understudied. There is a paucity of empirical studies that investigate the actual energy consumption patterns of households and businesses under different electrification strategies, which is essential for understanding their climate implications. We therefore recommend that future empirical studies especially address the following types of questions: (i) What are perceived and actual barriers for the provision of higher tier energy services via off-grid electricity?; (ii) What factors explain the correlation (and heterogeneity of correlation), between on-grid and off-grid electricity supply and the appliances bought by households?; and (iii) What determines households’ selection of specific off-grid solutions, especially climate neutral renewables vs diesel generators? Furthermore, our sample reveals a need for more empirical research on Sub-Sahara Africa, which is an increasingly important region for electrification efforts. Finally, additional research on the local feasibility of, and barriers to, off-grid renewable energy deployment could further support the goal of sustainable development.

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Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: http://doi.org.10.7924/r42n55gltz.

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