Electricity access and rural development: review of complex socio-economic dynamics and causal diagrams for more appropriate energy modelling

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Abstract

The causal relationships between electrification and development of poor, rural communities are complex and contextual. The existing literature focuses mainly on the impact of rural electrification and electricity use on local socio-economic development, while the reverse feedbacks of various social and economic changes on electricity demand and supply have not been fully characterised. Most electricity access impact assessments assume linear, one-way effects and linear growth in electricity demand. However, the projections rarely match the reality, creating challenges for rural utilities. From a modelling perspective, the lack of attention to dynamic complexities of the electricity-development nexus prevents the appropriate modelling of electricity demand over time and, hence, informed planning for and sizing of power plants. With the goal to improve modelling of the electricity-development nexus, we undertake a comprehensive review and extensive analysis of the peer-reviewed literature on electricity access and its impact on rural socio-economic development, and vice versa. We characterise and describe the nexus between electricity access and development through graphical causal diagrams that allow us to capture, visualise and discuss the complexity and feedback loops. Based on this, we suggest guidelines for developing appropriate models able to include and simulate such complexities.

Our analysis confirms that electricity use is interconnected through complex causal relations with multiple dimensions of socio-economic development, viz. income generating activities, market production and revenues, household economy, local health and population, education, and habits and social networks. The causal diagrams can be seen as a first step of the conceptualization phase of model building, which aims at describing and understanding the structure of a system. The presence of multiple uncertain parameters and complex diffusion mechanisms that describe the complex system under analysis suggests that systems-dynamic *simulations* can allow

modelling such complex and dynamic relations, as well as dealing with the high uncertainties at stake, especially when coupled with stochastic approaches.

Keywords: rural electrification, electricity-development nexus, causality diagrams, energy modelling, complexities

Introduction

The International Energy Agency (IEA) estimates that 1,1 billion people do not have access to electricity, most of them living in rural areas (International Energy Agency 2017). Lacking reliable access to electricity is considered a limit on people's opportunities and quality of life. The role of energy as a key driver to sustainable development is now widely recognized by the global community, as evidenced by the fact that the Sustainable Development Goals (SDGs) include access to affordable, reliable, sustainable, and modern energy for all by 2030 as an explicit target. While the relationship between electricity use and development is known from a macroscopic and macroeconomic point of view, the local dimensions of the electricity-development nexus in poor, rural contexts are not completely captured and characterized. Experiences of international institutions like GIZ and the Energy Sector Management Assistance Programme (ESMAP) of the World Bank have highlighted the multifaceted aspects of the issue. They have shown that it is not enough to simply provide people with access to electricity and "hope for local economic activity to pick up by itself" ((Brüderle et al. 2011) pg. 8). Indeed, the literature emphasises that electricity access should always be accompanied and sustained by other enabling activities and services, in order to contribute to greater educational attainment, more business opportunities, and higher income at the local level (Bastakoti 2003; Colombo et al. 2013; Khandker et al. 2013). Against this backdrop, in this paper we review the complex nexus between electricity access and use, and socio-economic development of rural areas in the Global South.

The complexity of the problem renders the use of linear or pre-defined sets of relations of cause and effect to describe the issue inaccurate, since "the dynamics of growth and electrification are complex, involving many underlying forces" ((Khandker et al. 2013) pg. 666). According to Matinga and Annegarn, "simple deterministic relations between electricity access and development outcomes do not reflect reality" ((Matinga and Annegarn 2013) pg. 301), while Ahlborg (Ahlborg 2015) confirms the presence of multiple interfaces and feedbacks that shape outcomes in electrification processes. The literature also suggests that the nexus between electricity use and rural socio-economic development has dynamic components, meaning that the nexus is characterized by complex feedbacks that can reinforce or balance impacts over time (Ulsrud et al. 2011). Khandker's (Khandker et al. 2013) study of Vietnam's rural electrification program exemplifies how a "virtuous circle of development" emerged as significant investments in other rural infrastructure services were undertaken (viz. water supply, roads, health and education) and rural electrification contributed to greater educational attainment, more business opportunities, and higher income, which in turn improved the affordability of electricity and appliances, leading to an increase of total electricity load and more investments in rural electrification. Khandker, as well as others (Kanagawa and Nakata 2008), suggest that electrification, if supported by enabling complementary actions, can lead to positive feedbacks on future electricity demand in a rural context.

In rural electricity planning, being able to analyse and forecast electricity demand is pivotal to the development of sustainable and reliable electricity models and plans, especially those dealing with the architecture and sizing of off-grid solutions. Inaccurate predictions can negatively impact local socio-economic development and cause unsustainable sizing processes of energy solutions, leading to negative consequences for the technical performance of the power supply (Ulsrud et al. 2011), such as supply shortages or cost recovery failures (Hartvigsson et al. 2015). Existing energy demand models for off-grid electricity planning do not capture these complexities; indeed, they usually rely on simple estimates of the energy demand and its evolution over time. Given that such linear projections are commonly inaccurate, being able to understand and model aspects and dynamics that determine rural electricity use can lead to more robust energy planning and solutions in rural areas, as well as increase the current understanding of the energy-development nexus.

The goal of our study is therefore to:

(i) review and analyse literature which describes, explains, and discusses – through case studies, experiences on the field, and surveys – the impact of electricity access and consumption on rural socio-economic development, and vice versa;
(ii) discuss and capitalize on the literature's findings by describing the development nexus complexity through graphical representations – viz. causal diagrams (Coyle 2000).
(iii) derive insights and set useful guidelines for developing appropriate models able to include and simulate such complexities.

With this work, we try to make explicit the many aspects that influence electricity use and demand – that "energy problems go beyond purely technical and economic issues" ((Morante and Zilles 2001) pg. 380). Our intended audiences are researchers in energy and socio-economic development, energy modellers, energy planners and policy makers involved in the global challenge of rural electrification. In particular, we aim at providing researchers and modellers with useful guidelines for developing robust long-term energy access scenarios; while we wish to provide the latter with a clearer view of the multifaceted and interrelated techno-economic and social complexities at stake, and consequent useful information for enhancing effective and sustainable electricity access polices.

1. Background - Electricity access and rural development

1.1. State-of-the art

In this section, we report the state of the art for review studies that focus on electricity access and rural development, trying to highlight the methodological progress achieved in the years and the new emerging challenges. Reviews studies of the socio-economic impacts of rural electrification in developing economies and formerly colonized countries started emerging in the 1980s. Within the context of the International Labour Office's World Employment Programme's research, Fluitman published a working paper in 1983, where he reviewed the available literature on rural electrification, its effects on rural industrialisation, and its impact on such socio-economic objectives as employment and income generation. The paper concluded that the socio-economic benefits of providing people with access to electricity in rural areas seemed to be overestimated. Also, he saw a need for "more judicious planning, formulation and evaluation of rural electrification programmes (pg. v)" for maximising the positive impacts of electrification-oriented investments.

In more recent years, other review papers on this topic have been published both in the grey and scientific literature. There is also an increasing interest in the impacts and sustainability of renewable energy based decentralised electricity provision. Among the grey literature, many country- or region- specific reports and evaluations papers are from donor organizations (World

Bank 2002; Khandker et al. 2009a, 2009b, 2012; UNDP Asia-Pacific 2012). The first chapter in the joint GIZ-ESMAP study "Productive Use of Energy" (PRODUSE) is a review of the impact of electricity access on economic development (Attigah and Mayer-Tasch 2013). Their main conclusion is that, despite a growing body of literature that indicate positive impacts of both electricity use and electricity quality on firm productivity, the magnitude of such impacts is highly country- and context-specific. In their report produced for UK Department for International Development, Meadows et al. (Meadows et al. 2003) provide an overview of the impacts of modern energy on micro-enterprises in developing economies. In accordance with the PRODUSE study, they also conclude that "modern energy can, but does not necessarily, affect the emergence, development, productivity and efficiency of micro-enterprise" ((Meadows et al. 2003) pg. 23). The Independent Evaluation Group (IEG) (Independent Evaluation Group (IEG) 2008), an independent unit within the World Bank Group, published a well-known document, which reviews the methodological advances made in measuring the socio-economic benefits of rural electrification on local communities in low-income countries. They concluded that electrification can have positive impacts on local communities, in terms of growth of local income generating activities, time-savings, educational and health improvements, but such results lack a quantitative scientific evidence base. In their World Bank working paper, Bacon and Kojima (Bacon and Kojima 2016) review the methods, findings and robustness of studies reporting strong links between energy, economic growth, and poverty reduction. Their goal is to support project teams and practitioners in identifying reliable studies without serious methodological or data problems.

In the scientific literature, reviews examine the cumulative evidence base as well as the methodological basis for measuring impacts. The survey by Ozturk (Ozturk 2010) focuses on the causal relationship between electricity consumption and economic growth at country-level, by investigating papers that employ econometric approaches to find relations between national GDP and electricity consumption (EC) indicators. Cook (Cook 2011) reviews the literature on the role and relation of electricity infrastructure in rural areas on economic growth and social development. Brass et al. (Brass et al. 2012) offer a comprehensive review on the main outcomes – viz. short- and long-term economic, educational and health implications – of distributed generation (DG) projects and programmes in developing countries. More recently, the same authors (Baldwin et al. 2015) have expanded their review on DG and rural development to cover the issue of scale in distributed energy systems. Terrapon-Pfaff et al. (Terrapon-Pfaff et al. 2014) evaluate the impact and the sustainability of 23 small-scale renewable energy projects in developing countries, suggesting that the majority of the projects had positive effects on sustainable development.

1.2. Novelty of the work

This review contributes a uniquely comprehensive overview of the complex causal relations between electricity access and socio-economic development. Based on our review, we find that the existing grey and scientific literature focus mainly on how rural electrification and electricity use affect local socio-economic development, while the reverse feedbacks are not systematically explored. Our review builds on the findings from existing reviews and studies, and it expands and adds the following novel elements: (*i*) an analysis of consequent feedbacks of socio-economic developments on electricity use and demand evolution over time, (*ii)* the representation – in terms of causal diagrams – of the insights that can be gained from the description of the dynamic complexities, and (*iii*) a discussion of the implications of the findings from an energy modelling perspective. Indeed, the electricity-development nexus is characterized by complex dynamic interactions, feedbacks, and behaviours. The understanding of such complex interactions requires therefore a more comprehensive investigation, which aims at analysing the "electricity-development nexus" as a *system* and not as a set of possible unidirectional correlations between multiple dimensions – i.e. electricity use and access on one side, and socio-economic indicators on the other.

1.3. Rationale and methodology

We reviewed 78 peer-reviewed articles using Science Direct editorial platform and Scopus databases (some statistics are reported in Figure 1 and Figure 2). We selected only case-studies (and reviews of them) that report and discuss in-depth qualitative and quantitative findings about the nexus between electricity consumption and socio-economic development at a local level. In accordance with Brass et al. (Brass et al. 2012), we excluded grey papers, reports and documents produced by intergovernmental organizations, NGOs, donors, and government agencies, as we believe their active role in electrification projects and programmes might have biased the reporting of results and potential failures. The only exception is represented by Meadows et al.'s review (Meadows et al. 2003), which covers an unusually wide range of case studies of rural electrification and reports quantitative data. We excluded studies that only cite anecdotal evidence from other sources, as well as papers that limit their focus to feasibility studies, cost-benefit analyses, and prospective studies. In terms of technologies, we evaluate the local electricity-development nexus by considering the implementation phases (viz. material supply, construction, start-up) as a given. This choice allowed us to consider any type of electrification solution, from small standalone-PV systems to grid-extension options.

We delimit the review to social and economic dimensions, where the cumulative evidence is quite substantive. Some important, but less well researched (Ockwell and Byrne 2016) dimensions are outside the scope of this paper: we exclude political and institutional variables from our causal diagrams, and we do not explicitly highlight how gender relations influence the dynamics, which they do across a range of issues (Winther 2015). However, modellers can investigate gendered outcomes, to the extent that gender disaggregated data are available.

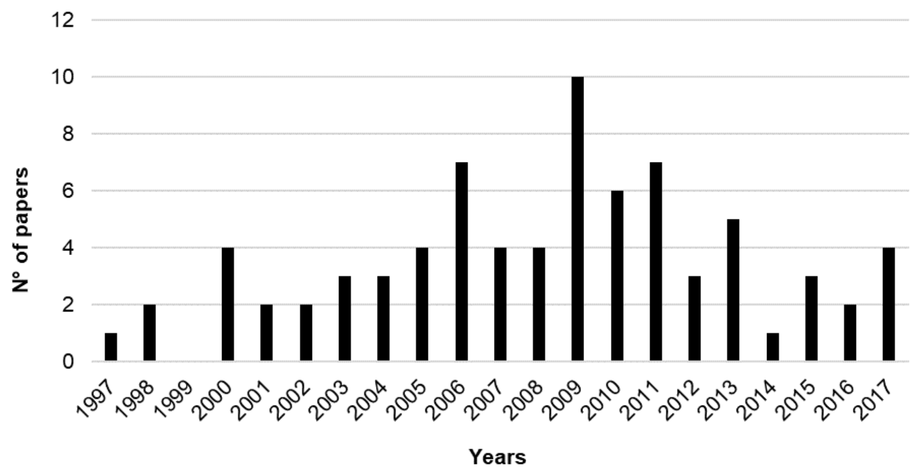

Figure 1. Publication years of the reviewed papers.

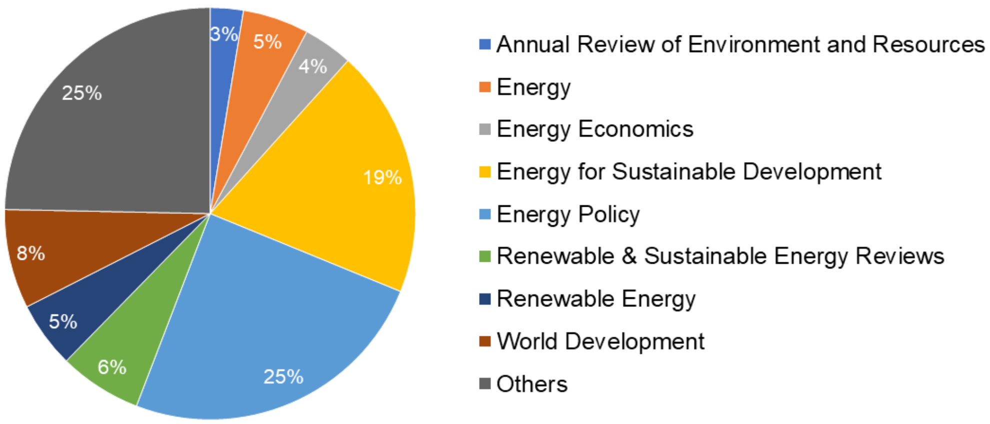

Figure 2. Journals in which the reviewed papers were published.

2. Review and analysis of dynamic complexities in the rural electricity-development nexus through causal diagrams

In this section we analyse the literature on the nexus between electricity demand and socio-economic development. We discuss and synthesize the main findings by representing the complex socio-economic dynamics through causal diagrams that highlight the reinforcing and balancing relations between the main variables characterising the nexus. Causal diagrams are conceptual models to represent complex systems, and therefore they include variables that are *meaningful* to people, but also *ambiguous* at the same time (e.g. the concept expressed by a variable can mean different things to different people (Luna-Reyes and Andersen 2003)). Section 3 proposes some guidelines for dealing with the formulation of possible models based on the qualitative variables conceptualized in causal diagrams. The variables in each diagram represent the different key-aspects of the electricity-development nexus mentioned in the literature. The arrows indicate the causal relationships; the positive "+" signs on the arrows indicate that the effect is positively related to the cause: an increase in the variable at the tail of the arrow causes the variable at the arrowhead to rise above what it would otherwise have been, in the absence of an increase in the cause. On the contrary, the negative "–" polarity of the arrows means that if the cause increases then the effect decreases.

From the literature, only two main dimensions of the nexus emerged clearly: (1) the *economic dimension* and (2) the *social dimension.* We analyse them separately, while we treat the impact of access to electricity on local environment as a cross-cutting dimension (e.g. household electrical lighting can cause less kerosene use, which decreases indoor air pollution with consequent possible improvements for household's health).

2.1. Economic dimension

The nexus between electricity demand and local economic development develops over time. In the following, we review previous literature and discuss three main sub-nexus through which economic development might impact on the structure of a local rural economy and future electricity demand: (i) the nature and amount of *income generating activities*, (ii) *production and revenues*, and (iii) changes to the *household economy*.

2.1.1. Income generating activities

With the term income generating activities (IGAs), we refer to all business activities and small-medium enterprises (SMEs) that provide a person with a regular or irregular cash-flow by selling goods and services, regardless of the type of the business, the size or the location. The potentially positive dynamics between electricity use and creation and spread of IGAs are reported and explained at different analytical levels within the scientific literature. In this sub-section, we organise the analysis of these dynamics into three different levels. First, we report on literature that indicates a positive linear impact of electricity use on the creation of IGAs, but without explaining it. Second, we discuss studies that report some causal reasons behind such potential impact, and third, we review literature that cover nexus dynamics including feedbacks between creation of new IGAs and electricity consumption. As expressed by Rao, "the causal effect of electricity supply on NFE [non-farm enterprises] income is complex, and both direct and indirect" ((Rao 2013) p. 535). Last, in this sub-section, we also summarize mechanisms that hinder a positive dynamic and suggestions made by scholars on how to enhance the development of rural IGAs.

The majority of papers simply state that access to electricity brings about an increase in local IGAs, especially the electricity-reliant ones. This portion of the literature lacks description of the complexity of the nexus, and they mainly report the spreading of IGAs after electrification in poor communities, as summarized in Table 1.

Table 1. Examples of impact of electricity use on IGAs' growth.

Reference	Mentioned impact of electricity use on new IGAs
Ravindranath et al. (Ravindranath and Chanakya 1986)	Access to electricity supported the creation of electric flour mills in Malanganj and B.N.Pura Indian villages
R. Kumar Bose et al. (Kumar Bose et al. 1991)	Access to electricity led to a 20% increase in business activities in three villages in Eastern Uttar Pradesh
B. Bowonder et al. (Bowonder et al. 1985)	Access to electricity led to the creation of repair and serving shops and village entertainment enterprises such as movie tents and community televisions (TVs) in eight rural communities in India
Cabraal et al. (Cabraal et al. 2005)	25% of households with electricity operated a home business in Philippines, compared to about 15% of households without electricity
Gibson and Olivia (Gibson and Olivia 2010)	Households connected to electricity increased their participation in non-farming enterprises by 13.3% in rural Indonesia, with the percentage of enterprises operated by rural households 43% higher after access to electricity
Mapako and Prasad (Mapako and Prasad 2007)	Results of the surveys on 73 small enterprises in the south west of Zimbabwe are reported with all the types and number of activities that were created after electrification; the total number of employees in these areas is reported to have been increased by 270%.
Bastakoti (Bastakoti 2006)	The Nepalese areas served by the Andhikhola Hydroelectric and Rural Electrification Centre (AHREC) experienced the creation of 54% more rural industries after electrification, allowing 600 more employees to have an income.
Prasad and Dieden (Prasad and Dieden 2007)	Data from South African national surveys suggest that somewhere between 40% and 53% of the increase in small, medium and micro-enterprises uptake is attributable to the grid roll-out.
Peters et al. (Peters et al. 2011)	The creation of electricity-reliant firms in regions with access in Rural Benin has been "a clearly positive effect of electrification" ((Peters et al. 2011) p. 781).
Jacobson (Jacobson 2007)	48% of the households interviewed in rural Kenya reported that the use of solar electricity supported some work- or income-related activities.
Adkins et al. (Adkins et al. 2010)	98.1% of adopters of solar lanterns in Malawi reported that the use of solar electricity supported some work- or income-related activities.
Kooijman-van Dijk and Clancy (Kooijman-van Dijk and Clancy 2010)	25% of households with electricity operated a home business in Philippines, compared to about 15% of households without electricity

At a second analytical level, some papers analyse the benefits of electrification on employment generation (related to construction, service provision and electricity use) in more detail by discussing the causal relations between access to electricity and the operation of rural economies. First, employment opportunities arise from the creation of new electrical infrastructures needed to satisfy local electricity demand and with the spread of new appliances and devices. In the causal diagram representing the dynamics between electricity demand and IGAs (Figure 3), this positive relation is represented by the link between *Electricity demand → Off-grid system related organizations → IGAs*. Studies such as those by Kumar et al. (Kumar et al. 2009) and Somashekhar (Somashekhar et al. 2000) report the creation of organizations in charge of manufacture, installation, operation and maintenance of new power generation infrastructures in India. Biswas et al. (Biswas et al. 2001) suggest that the operation, maintenance and administration activities of renewable energy technologies can bring positive impacts on the rural employment rate in Bangladesh. Second, an effect of rural electrification is the freeing up of time thanks to the use of electric appliances and services (instead of manual labour), especially for women who can use more time for home production (Grogan and Sadanand 2013; Khandker et al. 2013) and market activities (Dinkelman 2011). The time savings allow for the establishment and extension of IGAs as mentioned in (Bastakoti 2006; Mulder and Tembe 2008; Kumar et al. 2009; Gurung et al. 2011; Sovacool et al. 2013). This dynamics is represented through the positive *Electricity demand → Free-time → IGAs* links. Finally, Dinkelman (Dinkelman 2011) indicates that South African electrification affected rural labour markets also by facilitating new activities for men and women, who started producing market services and goods at home through the adoption of new electrical appliances (*e.g.*, food preparation, services requiring electric appliances) – positive *Electrical machines and devices → IGAs* link.

At a third level of analysis, some literature delves in more depth and investigates the propensity to establish new activities, invest in and extend IGAs, and the related feedbacks on electricity demand. As already highlighted, the possibility to use electrical devices makes new activities possible and for people to invest in: telephone booths, shops that produce and sell yoghurt, fresh drinks (Kirubi et al. 2009; Sovacool et al. 2013), ice-cream (Bastakoti 2006), office support services – e.g. faxing, word processing, photocopying, printing shops, computer centres (Lenz et al. 2017) – , energy stores, laundry services, hair dressers, photo studios (Bastakoti 2006; Shackleton et al. 2009; Peters et al. 2011), saw mills, welders (Peters et al. 2011), village entertainment enterprises such as movie tents and community TVs (Bowonder et al. 1985; Bastakoti 2006), cold stores (Bastakoti 2006; Matinga and Annegarn 2013) – the positive *Electrical appliances availability → Propensity to invest → IGAs* link. Related to this, the diffusion and use of new electrical appliances and machines both require and allow the establishment of new small business activities that can offer regular maintenance and charging services (*Electricity demand → Local maintenance services*), as reported for rural Eritrea (Habtetsion and Tsighe 2002), Mali (Sovacool et al. 2013) (Moharil and Kulkarni 2009) (Meadows et al. 2003), and India (Bowonder et al. 1985). The presence and availability of local maintenance, in turn, encourages people to invest in electrical machines for starting new income generating activities, because of the easy access to repair services (Cook 2011) – positive *IGAs → Local maintenance services → Propensity to invest → Electrical machines and devices → IGAs* reinforcing loop. Thus, causal relationships are identified between the generation of new IGAs, development of maintenance services, people's willingness to make investments in electric devices and machines and further growth in electricity load – *IGAs → Local maintenance services → Propensity to invest → Electrical machines and devices → Electricity demand*.

What the literature also highlights is how the decision to set up a new business activity is highly dependent on the financial resources of people and their capability to mobilize these (Meadows et al. 2003; Ahlborg 2015) – this is the reason why income increases from businesses or employment favour especially rich and middle income households (Jacobson 2007; Cook 2011; Kooijman-van Dijk 2012; Khandker et al. 2013; Matinga and Annegarn 2013) and increase economic inequality. Investment barriers often hinder poorer households from starting small businesses (*IGAs → Income inequality → Access to financial capital*). As a consequence, income is a pivotal driver of the decision to invest in new IGAs and new electrical devices to support businesses (Obeng and Evers 2010). Therefore, increasing the income earning opportunities and revenues, or reducing costs – for a larger part of the population – related to electricity use has a direct positive feedback on potential new investments in productive electricity demand (Ahlborg and Sjöstedt 2015) – the positive *IGAs → Average Income → Access to financial capital → Propensity to invest → Electrical machines and devices* feedback on *Electricity demand*.

Importantly, a significant portion of the literature is sceptical of the positive effects of electrification on the establishment and expansion of new IGAs (Stojanovski et al. 2017). The main reason provided by these studies is the high poverty and inequality level, which usually characterizes these contexts. As stated by Ahlborg and Hammar (Ahlborg and Hammar 2014), as long as a majority of people live below or close to the economic poverty line, the potential for beneficial dynamics between electricity access and local business and industrial development is very limited. Alazraki and Haselip (Alazraki and Haselip 2007) report that only 3% of people interviewed in rural provinces of Jujuy and Tucumán, Argentina, stated that access to electricity through PV-powered SHS allowed them to start a new business. Kooijman-van Dijk and Clancy state that employment opportunities as a consequence of access to electricity in Bolivian, Tanzanian and Vietnamese villages consist mainly of flexible and “unpaid involvement of family members” ((Kooijman-van Dijk and Clancy 2010) p. 18). Lenz et al. (Lenz et al. 2017) indicate that the majority of rural Rwandan households they interviewed were still farmers after electrification, with no significant changes in IGAs before and after electrification. One of the most recurrently identified obstacles to the expansion of rural business is the lack of a dynamic local market (Neelsen and Peters 2011; Kooijman-van Dijk 2012; Baldwin et al. 2015), leading to the “crowding out effect” of the existing firms, i.e. the creation of new IGAs that is followed by stagnation or economic losses among already existing IGAs (Kooijman-van Dijk and Clancy 2010; Peters et al. 2011), or a reduction of wages due to an abundance of labour supply over labour demand (Dinkelman 2011). We represented this effect through the positive link *IGAs → crowding out* which negatively affect the *Average Income* variable. In some contexts, the lack of credit for investment in new electrical equipment and grid connection represents a barrier to the set-up of new activities (Bhattacharyya 2006; Grimm et al. 2013). For example, some entrepreneurs in rural Benin could not electrify their manufacturing processes because of the high cost for changing to more modern electricity-driven technologies (Peters et al. 2011); and more than three quarters of entrepreneurs interviewed in two rural communities near Lake Victoria in Uganda said that grid connection has too high a break-even point on the return on investment (Neelsen and Peters 2011). Peters et al. (Peters et al. 2009) suggest that when there is a single-person business, electric machinery may have an hourly cost higher than human labour. This confirms that the lack of *Access to financial capital* discourages people in setting up or modernizing their business, i.e. it reduces people’s *Propensity to invest* and consequently the diffusion of new *Electrical machines and devices*. The decision to start a new activity and the consequent expansion of IGAs is also sometimes limited by the low quality of electricity supply (the negative *Power unreliability → Propensity to invest* link). Gibson and Olivia (Gibson and Olivia 2010) report that households in Indonesian villages, which never suffer blackouts, have an average of 1.3 more non-farm enterprises than in villages with frequent black-outs.

In order to overcome such barriers, several papers propose some complementary activities and actions to enhance the positive impact of electrification on the development of new IGAs, especially where no business “stemmed from electrification itself” ((Matinga and Annegarn 2013) p. 299). This is especially important in order to support women entrepreneurs who in many countries find it harder than men to mobilise financial capital (Ellis et al. 2007). These exogenous activities are represented through dashed red arrows in the diagram of Figure 3. Facilitating access to credit and finance is the most common recommendation (Biswas et al. 2001; Bastakoti 2006; Adkins et al. 2010; Kooijman-van Dijk and Clancy 2010; Gurung et al. 2011; Peters et al. 2011; Brass et al. 2012; Baldwin et al. 2015), since it allows people to set-up new IGAs, and facilitates a regular cash-flow, which in turn helps build financial capital (Bastakoti 2006) (*micro-credits → Access to financial capital*). Several studies (Bastakoti 2006; Cook 2011; Kooijman-van Dijk 2012; Sovacool et al. 2013; Baldwin et al. 2015) encourage stimulating the development of local markets and demand to decrease the crowding out effect (*market stimulation → Market demand → crowding out*) and increase people’s willingness to invest in new business opportunities (*market stimulation → Market demand → Propensity to invest*), and disseminating new technical skills through educational activities, business and manufacturing training for supporting the start of new IGAs (*capacity building → IGAs*). Providing access to accessible roads (*infrastructures → Market demand*) is also mentioned as a complementary activity (Kirubi et al. 2009; Gibson and Olivia 2010; Kooijman-van Dijk and Clancy 2010).

Figure 3 represents the dynamics described above, highlighting the positive and negative feedbacks among variables, as well as indicating the complementary activities and conditions that positively enhance the dynamics. From this we learn that electricity demand in poor rural areas is characterised by variables that are highly interdependent, suggesting that the literature should put more emphasis on this aspect. The diagram indicates that the propensity to invest is a key-aspect affecting the growth of future electricity demand and the creation of new IGAs. Further, the diagram shows that people’s propensity to invest is positively affected by their financial capacity (which increases, if average income increases), the availability of electric machines and a local reliable maintenance service, and the growth of local market demand for goods and services. In particular, in case of investments in an electricity-reliant business, the “propensity to invest” variable signifies both the start of new electricity consumer-IGAs, as well as increased demand from existing electricity consumer-IGAs that expand their business by investing in more appliances and machinery.

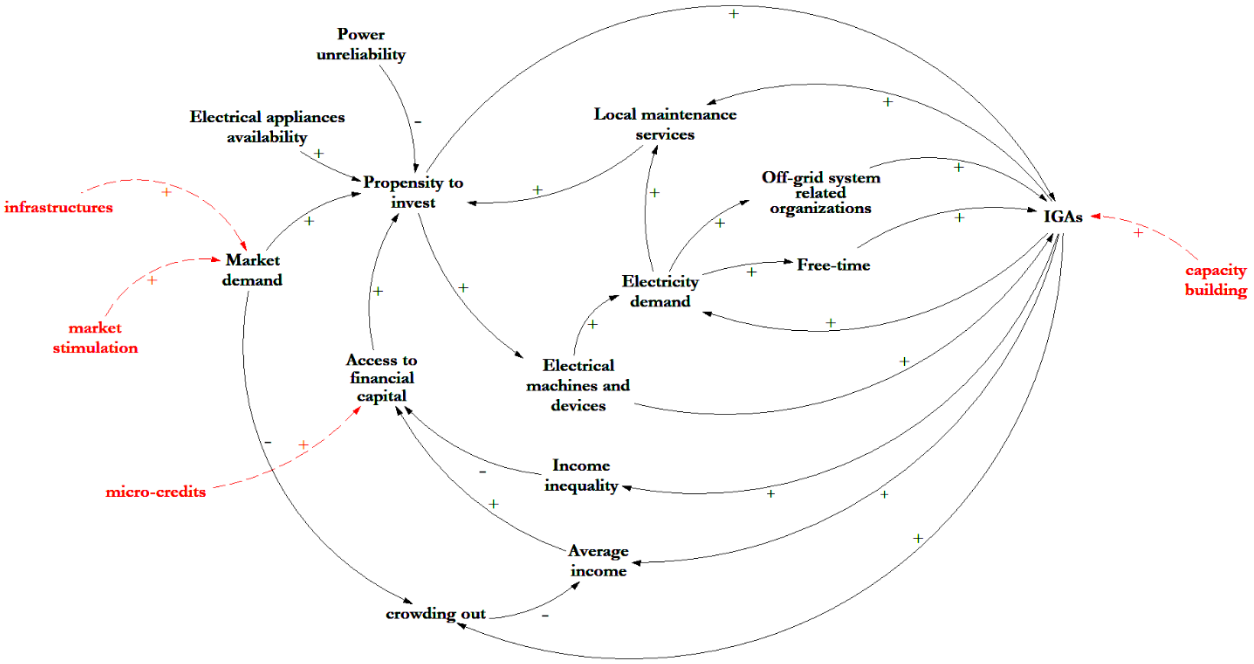

Figure 3. Causal-loop diagram representing the dynamics between electricity demand and IGAs.

2.1.2. Market production and revenues

The second sub-nexus we identify between access to electricity and economic impacts, is through local market production by IGAs and local revenues. We discuss the potentially positive dynamics of electricity demand and market production through different levels of analysis. First, we report on literature that indicates a positive potential impact of electricity demand on the productivity in local markets. Next, we discuss studies that analyse the impact of electricity use on the local markets – *viz.* the effect of electricity demand on market *demand* and *supply*. In the case of literature reporting low or no impacts, we highlight some complementary activities from the literature that might enhance the benefits of electricity on the operation of local markets. Finally, we review what feedbacks have been identified between local market production and electricity demand in the literature.

Our first level of literature analysis suggests that electricity use increases local production and people's productivity, especially in new electricity-reliant businesses, as exemplified in Table 2.

Table 2. Examples of impact of electricity use on market production and revenues.

Reference	Mentioned impact of electricity use on market production and revenues
Ranganathan and Ramanayya (Ranganathan and Ramanayya 1998)	An extra kWh of electricity generated an incremental surplus of agricultural production for Indian farmers
Meadows and Kate (Meadows et al. 2003)	In India, energy-intensive enterprises that obtained access to modern energy achieved enhanced income levels of 30-40% more than enterprises that did not gain access.
Peters et al. (Peters et al. 2011)	In villages located in Northern Benin, the profits of connected firms were considerably higher, *viz.* 73.8% higher (statistically significant at the 5% level), than those of non-connected firms, and this is especially true for electricity-reliant firms.
Kooijman-van Dijk (Kooijman-van Dijk 2012)	It is found a positive relation between 'electricity use for enterprise products and services' and income from enterprises in the Indian Himalayas, although electricity is not considered the definitive solution to poverty reduction.

Gustavsson (Gustavsson and Ellegård 2004; Gustavsson 2007a)	In Zambia, lighting in the evening could improve teachers' income, enabling them to earn some extra income by teaching in the evening.
Cabraal et al. (Cabraal et al. 2005)	Households managing small cottage industries in rural India were able to increase their daily income using electric lighting to extend their productive hours after nightfall.

The studies that focus on the dynamics behind the possible increase in enterprises' productivity and revenues suggest that access to electricity and use may positively or negatively impact local markets by affecting local *supply* and *demand* of goods and services.

Market demand

Focusing on local market demand, the number of consumers for a given business may increase thanks to the increased use of communication devices and advertisements (Jacobson 2007) (*Electricity demand → Communication devices → Market demand*). Communication devices – e.g. TVs, radio and phones – may also introduce changes in aspirations and expenditures of rural households (Matinga and Annegarn 2013) for goods and services, diversifying purchases and leading people to shop locally rather than elsewhere (Shackleton et al. 2009). Neelsen and Peters (Neelsen and Peters 2011) report that electric lighting and the consequent increase in perceived security attracted potential customers also during the evenings in rural Uganda. Kirubi et al. (Kirubi et al. 2009) and Kooijman-van Dijk (Kooijman-van Dijk 2012) suggest that electric appliances allow for improvements in products' quality (*Electricity demand → Product quality → Market demand*) and production and/or selling of new products (*Electricity demand → Product innovation → Market demand*) which can attract more consumers or increase the demand per-capita, with positive impacts on local production and the consequent revenues (*Market demand → Goods/services sold → Net revenues*). In this context, Peters et al. highlight the risk that "to the extent that local consumer's purchasing power is diverted to the new electricity-reliant manufacturers, existing non-reliant manufacturers are likely to suffer a drain on business" ((Peters et al. 2011) pg. 778), increasing inequality.

Multiple studies report that such increases in the demand for products and services in turn causes an increase in price, due to market equilibrium rules (Meadows et al. 2003; Cabraal et al. 2005; Sovacool et al. 2013). However, this conventional equilibrating market mechanism does not always appear to apply in developing economies – as Banum and Sabot (Barnum and Sabot 1977) report for Tanzanian rural markets – which raises questions about the actual impact of improvements in products' quality on the price of goods.

Market supply

On the production-side, there are four mechanisms whereby electricity use can have a positive impact: (i) enhancing communication, (ii) enhancing work productivity, (iii) enabling longer work days, and (iv) decreasing energy-related costs. First, communication devices help improve the efficiency of business activities and the related market revenues (*Electricity demand → Communication devices → Production efficiency → Net revenues* in Figure 4). Cabraal et al. (Cabraal et al. 2005) report that the use of telephones in rural Thailand enabled farmers to regularly check prices in Bangkok and significantly increase their profits, while the use of the internet by Indian farmers allowed them to obtain current information on market prices and good farming practices, and consequently order appropriate agricultural inputs. Jacobson (Jacobson

2007) suggests that Kenyan owners of business activities benefited from receiving regular business information via television and radio, while the use of cell phones helped retail shops and other service-oriented businesses to place orders, make business deals, be in contact with their clients, and finally increase sales. This positive outcome of electricity use for productive purposes has been highlighted also by Khandker et al. (Khandker et al. 2013) for Vietnam.

Second, the use of electric machinery and appliances can help increase productivity, i.e. the number of products and services that an enterprise can supply in a given time period, which in turn increases the supply of goods to the local market. However, if the demand stays equal, it generates a drop in the price of goods, which can be offset by an increase in the volume of sales made (depending on the type of product/service), in turn increasing revenues (*Electricity demand → Productivity → Market supply → Goods / services sold → Net revenues*). Kirubi et al. (Kirubi et al. 2009) report that the small-medium enterprises in a community-based electric micro-grid in rural Kenya experienced a significant increase in revenues in the order of 20–80%. Kooijman-van Dijk (Kooijman-van Dijk and Clancy 2010; Kooijman-van Dijk 2012) indicates that, when the market-demand is high, tailors that used electric sewing machines were able to increase the productivity by two to three times more than the average, while grain millers reported processing larger volumes of grains per day. The increase in demand for higher-quality products and services supplied by the use of electric machinery may enable sellers to fetch higher prices and increase revenues (Meadows et al. 2003; Kooijman-van Dijk 2012; Sovacool et al. 2013). On the other hand, an increase in productivity brought about by access to modern machines may decrease the need for human resources, causing a decrease in the employment rate and individual revenues (the negative *Productivity → Human labour → Average income* feedback): Meadows et al. (Meadows et al. 2003) report that in rural Indonesia, the introduction of a wind power pump reduced human labour input by a factor of 10, from 1040 to 100 hours.

Third, access to electricity may improve sales and businesses by extending operating hours thanks to lighting (Alazraki and Haselip 2007; Mishra and Behera 2016) (*Electricity demand → Evening work time → Market supply*). Meadows et al. (Meadows et al. 2003) state that the introduction of battery-operated lamps in rural Bangladesh allowed tailors to work for four more hours and thereby increase their revenue by 30%, while rice milling activities were performed during 7 to 9 p.m. in Hosahalli village (India). Agoramoorthy and Hsu (Agoramoorthy and Hsu 2009) report on the experience of some households in India, who suggest that lanterns provide opportunities to expand business and allow more time to work at night when compared to fuel-based lighting sources. Jacobson (Jacobson 2007) suggest that lighting in the evening can benefit and positively impact teachers' income in rural schools in Kenya, enabling them to grade papers, plan evening lessons at home and earn some extra money. Similar increases in productive hours during evenings are reported by Komatsu et al. (Komatsu et al. 2011), who report that households in the rural districts of Comilla, Kishoreganj, and Manikganj in Bangladesh extended their working hours by about two or more hours in the evening, while 56% of connected firms surveyed by Peters et al. (Peters et al. 2009) in Copargo (Benin) declared working longer thanks to lighting that extended their daily operating hours. The same effect of night-lighting was reported by Chakrabarti (Chakrabarti and Chakrabarti 2002) and Baldwin et al. (Baldwin et al. 2015), who indicated that, in Sagar Dweep island in West Bengal (India), shopkeepers and workers engaged in handicrafts extended their working hours in the evening. The increase of daily working hours is especially common for commercial activities located in residential areas, where the demand is higher (Neelsen and Peters 2011), shops and barbers (Meadows et al. 2003; Kooijman-van Dijk and Clancy 2010), and restaurants, whose increasing in operating hours has a direct impact on revenues (Kooijman-van Dijk 2012).

Several papers are also sceptical about the positive effects of electrification on the extension of operating hours. For example, Adkins et al. (Adkins et al. 2010) state that less than 10% of solar lantern users experienced expanded business opportunities by working more at night. In rural Indian Himalayas, only half of entrepreneurs with access to light worked regularly in the evening (Kooijman-van Dijk 2012), because of structural barriers, such as distance from main roads or time limitations of workers. In some cases, evening light is considered merely a means of guaranteeing more flexibility at work (Kooijman-van Dijk and Clancy 2010; Kooijman-van Dijk 2012). Moreover, for producing enterprises, increasing working hours does not result in new consumers, but simply increases production volumes (Kooijman-van Dijk 2012). Sometimes, an increase in productivity as a result of more efficient machines may even reduce working hours (Kooijman-van Dijk and Clancy 2010) (the negative *Productivity → Evening work time* feedback). These findings suggest that two determining factors for increasing night operation may be the availability and reliability of electricity during night hours (Kooijman-van Dijk and Clancy 2010; Obeng and Evers 2010) (the negative *Power unreliability → Evening work time* feedback) and market demand (*Market demand → Evening work time*).

Fourth, there is evidence that the use of electricity for productive purposes may increase profit margins by reducing the cost associated with other energy resources (Habtetsion and Tsighe 2002) (*Electricity demand → Traditional sources of energy → Energy cost → production efficiency → Net revenues*). Matinga and Annegarn (Matinga and Annegarn 2013) report that some shopkeepers experienced a marginal reduction of operational costs associated to refrigeration, since they found gas more expensive than electricity. Electricity may be cheaper than diesel for running machinery, as evidenced in Mawengi (Tanzania), where electric milling machines significantly reduced the cost of milling the staple maize in comparison to the previous use of diesel-powered machinery (Ahlborg 2015). In Vietnam, milling 1 ton of rice with diesel costs at least four times more than by using electricity (*viz.* US$ 2.6 against US$ 0.6) (Kooijman-van Dijk and Clancy 2010). In the Syangja District in the western region of Nepal, an electric mill could reduce costs by 30-50% with respect to diesel-powered ones (Bastakoti 2003). Sometimes, savings are attributable to a shift from grid power supply to stand-alone or microgrids (Kumar et al. 2009). However, fuel-shifting may sometimes cause higher expenditures for the producer (*Power unreliability* increases *Energy cost*).

As a matter of fact, energy-cost savings are extremely dependent on the quality of electricity supply, since unreliable access to electricity – i.e. frequent black-outs, high voltage fluctuations and frequency instability – may negatively impact productivity and cause huge economic losses (Kooijman-van Dijk 2012) and very low satisfaction with electricity supply (Aklin et al. 2016), as well as the need to pay for back-up energy options like diesel. In rural Indonesia, power supply unreliability reduced the number of activities operated by each household (Gibson and Olivia 2010). Zomers (Zomers 2003) and Meadows et al. (Meadows et al. 2003) report unreliable energy service as one of the main problems that entrepreneurs in rural areas encounter. Unreliable or expensive electricity can, hence, increase the cost of production leading to an increase in price and consequent decrease of market demand and sales. Such drawbacks related to service quality and cost may deter entrepreneurs from gaining access, as in the case of rural Uganda (Neelsen and Peters 2011).

In light of the discussion above, we can identify factors and feedbacks that explain how electricity use can either positively boost, or have a little impact on, economic production at the local level. In order to enhance electricity-related productivity, the literature indicates the need for complementary activities and certain preconditions. First of all, reliable electricity supply is a key factor for enhancing the productivity of small-scale operators and rural enterprises (Meadows et al. 2003;

Wolde-Rufael 2005), highlighting the importance of appropriate operation and management activities (*appropriate O&M of power system* can reduce *Power unreliability* and in turn decrease the negative effect of unreliability on *Productivity*). Second, access to favourable credit terms can support the decision of local entrepreneurs to adopt new electrical devices, and therefore increase their production (Bastakoti 2003; Peters et al. 2009; Kooijman-van Dijk and Clancy 2010) (*micro-credits → Electricity demand*). A sustainable increase in production requires an accompanying increase in market demand (Peters et al. 2009), also in the evenings (Kooijman-van Dijk 2012). To facilitate such a development, other infrastructures such as roads and telecommunications need improvements, as these can reduce transactions costs and make rural IGAs “competitive in out-sourcing of business services and products destined for the lucrative urban markets”((Kirubi et al. 2009) p. 1219) (*infrastructures → Market demand → Goods/services sold*). For example, Lenz et al. (Lenz et al. 2017) report that in rural Rwanda, only rural communities located next to a main road and frequented by casual customers from outside experienced a net increase in income through sales of improved services and goods. In this context, capacity building plays an important role in supporting entrepreneurs’ social skills and networks to access new markets (*capacity building → Production efficiency*), and technical skills to innovate and sell products (*capacity building → Product innovation*) (Bastakoti 2006; Kooijman-van Dijk 2012).

Given the social, economic and geographical conditions of poor rural areas, the major impact of electricity use on local economies occurs when there is an increase in the net revenues or people’s incomes. Improved access to financial capital may result in a positive feedback on local electricity demand, enhancing positive dynamics at a firm-level, where net revenues can be invested in more electrical machinery (*Net-revenues → Average income → Access to financial capital → Electricity demand*) or in extending operating hours and business opportunities (*Net-revenues → Market supply*). A positive feedback can develop also at household-level if more income allows people to increase their expenditures, boosting the market demand for (new) goods and services, which in turn provides households with further opportunities to reduce costs and make money (Kooijman-van Dijk and Clancy 2010) (the reinforcing loop described by *Average income → Market demand → Goods/services sold → Net revenues → Average income*). The financial status of families is a pivotal parameter to consider for modelling their willingness to increase electricity load, especially in terms of appliance ownership. For example, Aklin et al. (Aklin et al. 2015) suggest a positive relation between income and electricity access by deriving econometrically the relation between household’s wealth, electrification status (*viz.* if an household has access to electricity or not) and hours of electricity used per day (for Indian households living in slums, urban and rural areas). We address the nexus between household economy and electricity demand more thoroughly in the next dedicated sub-section of the paper.

Figure 4 presents the causal loop diagram for electricity demand and market production and revenues. It visualizes the dynamics above, highlighting the positive and negative feedback among variables, as well as indicating the complementary activities and conditions that may enhance the dynamics (the dashed red lines). The main feedback on growth in electricity demand is an increase of people’s income and access to financial capital.

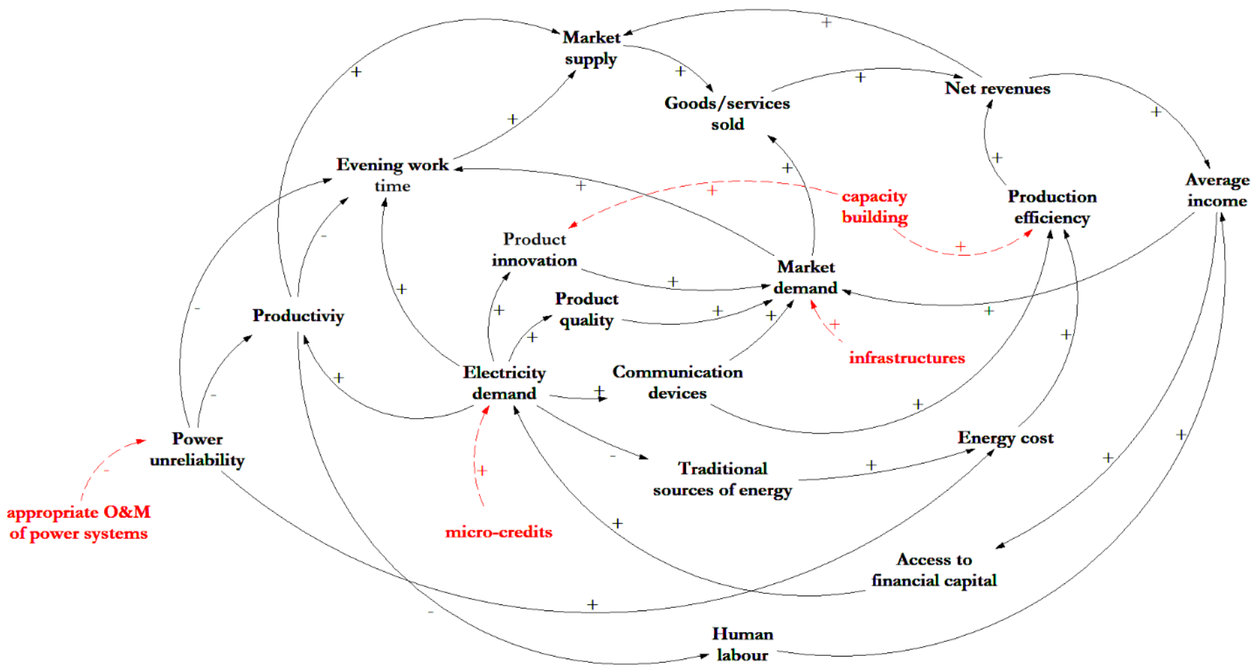

Figure 4. Causal-loop diagram representing the dynamics between electricity demand and local market production.

2.1.3. Household economy

In the previous sections, we identified a positive loop between increasing electricity demand, an increase in net IGAs and their sales of goods and services, which in turn can increase market revenues. Since the feedback of net revenues on electricity use involves domestic access to financial capital, in this sub-section we try to focus specifically on the nexus between electricity use and households' economy, which involve different dynamics than that related to business activities alone.

As a direct effect of the dynamics identified in the previous sections, the increase in market production and employment given by electricity use can boost households' financial capacity by a positive change in financial inflow (Ranganathan and Ramanayya 1998; Cabraal et al. 2005) (*Electricity demand → Net revenues → Income from IGAs activities* in Figure 5). Table 3 reports some examples from the literature, which suggests that access to electricity benefits the household economy, since electricity-reliant IGAs are more productive than their unconnected counterparts, in the range of 30% to 78% more, depending on the context. However, few studies provide statistically reliable estimates with appropriate intervals of confidence and clear definitions of the baseline used, reducing the reliability of data for modelling purposes.

Table 3. Examples of impact of electricity use on household economy.

Reference	Mentioned impact of electricity use household economy
Shackleton et al. (Shackleton et al. 2009)	Entrepreneurs who invested in small "productive use containers" powered by solar panels benefited from extra monthly sources of income in South Africa.
Sovacool et al. (Sovacool et al. 2013)	It is described the effect of the distribution of "multifunctional platforms", *i.e.* "small 8-12 horsepower diesel engines mounted on a chassis, to which various components can be attached" (pg. 117), in rural Mali. There, families experienced about 13.6% extra income per year (*viz.* about $68 in additional revenue per year per family, considering that the average household lives on $1.37 per day).
Gibson and Olivia (Gibson and Olivia 2010)	Income shares of non-farm enterprises (NFEs) are higher for rural Indonesian households that are connected to the public electricity network, *viz.* about 3.7% against 2.2%; it is indicated that the quality of power supply has a direct effect on income from productive

	activities, since the share of rural income from non-farm enterprises is estimated to be 27% higher for households in villages that never suffer blackouts (*Power unreliability → Average income*).
Balisacan et al. (Balisacan et al. 2003)	Households' income benefits are mainly experienced by richer families (*Income from IGAs activities → Income inequality*): a 10% improvement in access to electricity raised income among the poor by only 2%.
Rao (Rao 2013)	Through a multivariate regression, it is estimated that at the village level, access to at least 16 h of electricity per day might be responsible for 18% higher income for connected Indian NFE than non-connected ones. The study further finds that the expected income for an electrified household is 43% higher based on a propensity score matching model.
Bensch et al. (Bensch et al. 2011)	It is found a positive difference in income between connected and non-connected households in Rwandese electrified villages. It is also confirmed a difference in income also between connected households in electrified villages and households in non-electrified villages that they identity as "likely to connect to an electricity grid". Nevertheless, the robustness and significance of the results disappear when regional differences are accounted for, suggesting caution regarding the finding of a positive effect of electricity on income.
Khandker et al. (Khandker et al. 2013)	In 42 Vietnamese communes, household electrification is responsible for a growth of 21% and 29% in total and non-farm income, respectively. They found also a substantial spill-over benefit to non-connected households (*Electricity demand → Spill-over effect* feedback that reduces *Income inequality*).

Electricity use impacts also on households' *financial outflows*, *viz.* expenditures. As discussed in the previous sub-section, this is mainly due to improvements in products' quality and the availability of new products and services, following the modernization of production and other technologies (*Electricity demand → Product quality → Average market expenditures* and *Electricity demand → Product innovation → Average market expenditures*). It attracts more consumers and increase the per capita demand for some products and services (*Average market expenditures → Market demand*). Second, since households' expenditures depend on people's access to financial capital, the potential increase in family income has a direct effect on boosting the demand for goods and services (*Average income → Access to financial capital → Average market expenditures → Market demand*). Indeed, as Kooijman-van Dijk and Clancy (Kooijman-van Dijk and Clancy 2010) state, there must be a willingness to pay for the expected "new" goods and services produced by new IGAs. Khandker et al. (Khandker et al. 2012) indicate that electrification in India increased household per capita food expenditure by 14%, non-food expenditure by 30%, and total expenditure by more than 18%. Zhang and Samad (Samad and Zhang 2016) report lower results, suggesting that gaining access to the grid in India is associated with an 8.4% increase in households' per capita food expenditure, a 14.9% increase in per capita non-food expenditure, and a 12% increase in per capita total expenditure. Again, these positive results are also dependent on the reliability of access to electricity and the quality of power supply (*Power unreliability* decreases *Market demand*). Zhang and Samad indicate that every one-hour increase in power outages may decrease food expenditures by 0.2% on average, which in turn, potentially, reduce farmers' incomes. What these results indicate is that increase in household's access to financial capital can feed back on electricity demand, *i.e.* the increase in families' expenditures can in turn stimulate the modernization and electrification of market production and the use of electric lighting for evening work (*Access to financial capital → Average market expenditures → Market demand → Market supply → Electricity demand*).

Electricity use causes changes in people's expenditures for domestic energy supply. Considering lighting alone, the literature confirms that households experience a reduction in expenditures for energy use, especially for purchasing kerosene (Ulsrud et al. 2015; Grimm et al. 2017) (*Electricity* *demand* has a negative feedback on *Traditional sources of energy* that cause a reduction on *Energy cost expenditures*). Edwin et al. (Adkins et al. 2010) report that in rural Malawi, after the introduction of LED lanterns, lighting expenditures – all sources excluding the cost of the device – had fallen from $1.06 per week to $0.15 per week after lantern purchase. Similarly, Agoramoorthy and Hsu (Agoramoorthy and Hsu 2009) indicate that after the spread of solar lanterns in Indian Dahod District, each household saved on average $91.55 (±63.06, n=100) in energy costs per year, a huge saving if compared to households' yearly income ranging from $150 to $250. Wijayatunga and Attalage (Wijayatunga and Attalage 2005) report that when the cost for grid expansion is borne by the government, households in Sri Lanka are estimated to pay only $1 per month on average, which represents a relatively high cost saving if compared to the about $5.4 of avoided cost for kerosene usage and battery-charging. Lenz et al. (Lenz et al. 2017) report that households electrified by grid-extension in 42 rural communities in Rwanda experienced a reduction of one-third in their energy expenditures. A reduction of energy expenditures therefore means an increase in people's access to financial capital that can be allocated for more market or food expenditures (*Energy expenditures → Access to financial capital → Average market expenditures*), contributing to a positive feedback on local market production and electricity consumption.

However, the picture changes when the cost of power production technologies and non-lighting appliances are considered, with households experiencing sometimes an increase in energy expenditures after electrification (Davis 1998; Bensch et al. 2011)(Martinot et al. 2002) (*Electricity demand →Energy cost expenditures*). Wijayatunga and Attalage (Wijayatunga and Attalage 2005) report that for households that received a subsidy of about $100 for a solar home system (SHS) in Sri-Lanka, the monthly repayment of the system stood at $8.4 for a period of 5 years, that is, $3 higher than the cost of avoided kerosene usage and battery-charging – *i.e.* a little over 15% of their income was spent on the SHS repayment, whereas the expenditure on kerosene and battery-charging before SHS installation was only around 10% of their income. Komatsu et al. (Komatsu et al. 2011) indicate that households with a SHS spent more in total on energy supply than before, because of the monthly payments for the system, though the reduced costs of kerosene and rechargeable batteries account for 20–30% of the monthly payments. Moreover, kerosene saved by some households can represent a source of income if sold to non-electrified neighbours (Roy 2000). Wamukonya and Davis (Wamukonya and Davis 2001) state that Namibian households experienced a marked increase in energy expenditure after electrification. Indeed, whilst a shift from the use of candles and paraffin to electric lighting may decrease direct energy costs, the adoption and use of other appliances like irons, refrigerators, TVs, *etc*., can substantially increase the final energy bill. If the increase of energy expenditures is not supported by a proportional increase of income, it can cause a decrease in market expenditures and in turn a decrease in market supply and electricity use.

Income, therefore, plays an important role in defining the capacity of people to increase their electricity use and their willingness to pay for electricity (Kobayakawa and Kandpal 2014; Alam and Bhattacharyya 2017) (*Average income → Access to financial capital → Electricity demand*), especially in its two main constituents:

- **The installed load.** The literature suggests that the willingness of people to be connected, and to buy and own electrical household appliances, depends on their income. In their rural electrification model, Hartvigsson et al. (Hartvigsson et al. 2018) define the potential number of electrical connections as a function of different socio-economic parameters, including the average income of people. Lenz et al. (Lenz et al. 2017) state that the wealthier or more modern a household is, the more inclined it will be to get a connection. In their Residential Energy Model Global (REGM) applied to India, China, South East Asia, South Africa and Brazil, Ruijven et al. (van Ruijven et al. 2011) and Daioglou et al. (Daioglou et al. 2012) represent the diffusion and ownership of household electric appliances, through a logistic (or S-shaped) curve, as a function of household's expenditures (considered in their work as a proxy of income). Louw et al. (Louw et al. 2008) suggest that the use of electricity by low-income South-African households is a cost-based decision based on income, especially regarding the ownership of electrical appliances, which depends on prices of devices and people's affordability. The importance of appliances' costs in relation to people affordability is also pointed out by Prasad (Davidson et al. 2006).

- **The kWh of electricity consumed.** The quantity of electricity consumed is another aspect that might be influenced by people's income. Louw et al. (Louw et al. 2008) conclude that for South African households the demand for electricity shows elasticities[1] ranging from between 0.24 and 0.53, depending on the model. This low value is probably attributable to the subsidized tariff that makes electricity more affordable for the poor. Pachauri and Filippini (Filippini and Pachauri 2004) used disaggregate survey data for about 30,000 Indian households, and conclude that electricity is income inelastic in the winter, monsoon and summer seasons. They estimate that elasticity ranges between 0.60–0.64 across the three seasons. Tiwari (Tiwari 2000) derive similar results by analysing the income elasticity to electricity demand for the city of Bombay, estimating values ranging from 0.28 to 0.40 based on income group. Moharil and Kulkarni (Moharil and Kulkarni 2009) suggest that despite the higher cost of electricity, people living on Sagardeep Island in West Bengal demanded more power for entertainment, comfort and developing job opportunities irrespective of their income level, suggesting very low levels of demand elasticity. Alkon et al. (Alkon et al. 2016) use nationally representative household data from India, 1987–2010, and suggest that household income is not a primary determinant for willingness to pay for high-quality modern energy. Hence, the literature seems to suggest that electricity is income inelastic (*i.e.* the quantity of electricity demanded increase less than proportional to an increase in income), since it is often considered a basic need. However, the relatively high positive values estimated (between 0.24 and 0.64, depending on the context) suggest that an eventual increase in the economic status of people would lead to a rise in electricity consumption of households, although less than proportionally.

To enhance a positive feedback of household economy on electricity demand, the literature suggests some complementary activities to increase households' willingness to buy and use electricity. Among the recommendations, scholars suggest that electrification projects must be accompanied by sustainable "cost of connection" policies, such as international "smart" subsidies or cost-sharing mechanisms (Sovacool et al. 2013) for covering initial investments (Zomers 2003; Baldwin et al. 2015) (*cost of connection polices → Access to financial capital*). The importance of appropriate tariffs built into sustainable payment plans – like the pre-paid mechanism (Moharil and Kulkarni 2009) that allow people to pay up front, sometimes via their mobile phones, which reduces travel costs (Gustavsson 2004) – is also highlighted in the literature. Such plans can favour the poor (Bhattacharyya 2006, 2013). In this context, energy needs of rural communities should be considered top of the agenda of national energy policy making processes (Habtetsion and Tsighe

[1] "Elasticity is a measure of a variable's sensitivity to a change in another variable. In business and economics, elasticity refers to the degree to which individuals, consumers or producers change their demand or the amount supplied in response to price or income changes. It is predominantly used to assess the change in consumer demand as a result of a change in a good or service's price" (Source: (Investopedia, LLC 2014)).

2002), *e.g* through a proper regulation on energy pricing, taxes, laws and product standards on energy (Biswas et al. 2001). Further, the literature advise actors to create awareness among beneficiaries (*awareness activities → Electricity demand*), by first, creating demand for the "service" provided by energy technologies, rather than for the technology itself (Mulugetta et al. 2000), and second, involving the local community and consumers, especially women (Sovacool et al. 2013), in managing and operating energy systems (Sebitosi and Pillay 2005; Adkins et al. 2010; Sovacool et al. 2013; Terrapon-Pfaff et al. 2014). Complementary activities, thus, involve: (a) customer educational programmes (Sovacool et al. 2013); (b) the introduction and integration of some energy end-use services (e.g. lighting, pumping) into daily routines and practices (Somashekhar et al. 2000); (c) the implementation of demonstration initiatives designed to create knowledge regarding electricity use (Wamukonya and Davis 2001) and to boost demand for energy technologies (Baldwin et al. 2015), and; (d) the support for the widespread ownership of mobile telephones and accessibility of TVs sets (Matinga and Annegarn 2013) (represented through the positive *socio-economic grants → Access to financial capital → Electricity demand* feedback). Lastly, improving capacity building and access to information (know-how) on mechanical and technical matters at the household level – e.g. the basic understanding of the capacity of the system (Gustavsson and Ellegård 2004) – (*capacity building → Electricity demand*) as well as organizing reliable and competent customer service (Alazraki and Haselip 2007) and ensuring an appropriate O&M of the system (*appropriate O&M of power systems → Power unreliability*) are considered important drivers for growth of electricity demand.

Figure 5 describes these relations between electricity demand and households' access to finance, expressed through its two main determinants, *viz.* income and expenditures.

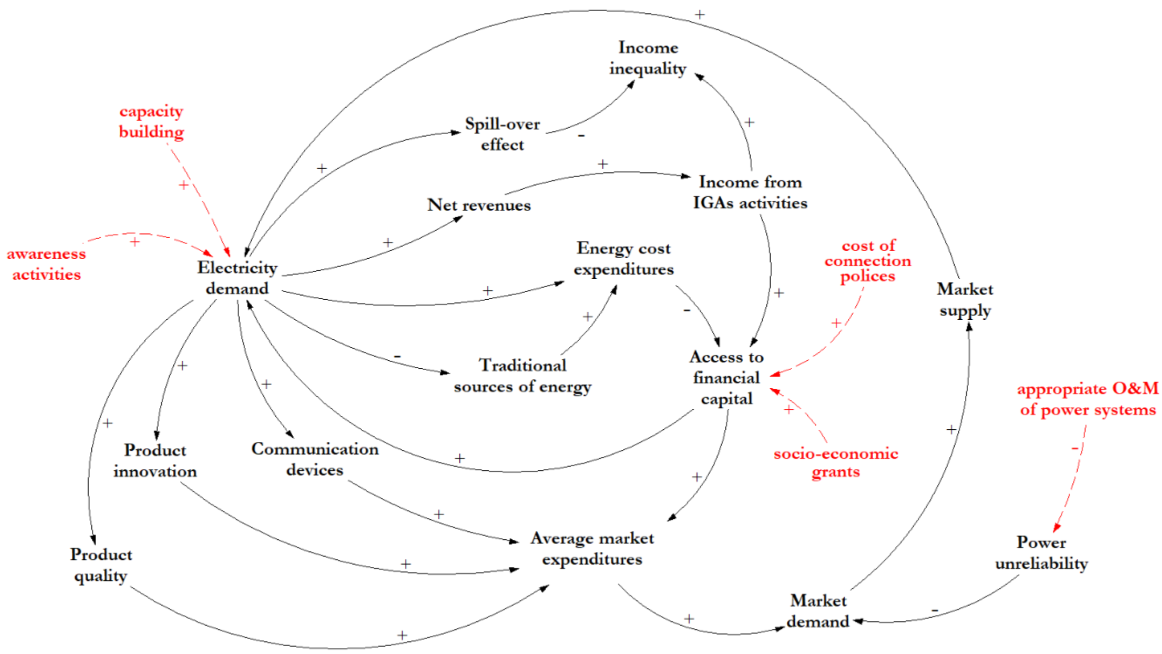

Figure 5. Causal-loop diagram representing the dynamics between electricity demand and household's economic availability.

2.2. Social dimension

In this section, we discuss the complex causalities between electricity demand and social dimensions of local development. In particular, we focus on three main aspects: (i) the dynamics of *local population* and *health*, (ii) *education*, and (iii) *habits, living standards and social networks*.

2.2.1. Local health and population

The literature suggests that increasing electricity access and use is beneficial to people's health (Wolde-Rufael 2005; Mulder and Tembe 2008; Sovacool et al. 2013) and can impact on local population dynamics. We discuss these dynamics by investigating the health dimension at the household, work and hospital level, and also by analysing the impact of electricity on local population growth and related feedbacks.

At a *household* level, access to electricity is reported to be an important driver for improved health of household members. For example, Wamukonya and Davis (Wamukonya and Davis 2001) indicate that respectively 49% and 35% of surveyed grid-electrified and solar-electrified rural Namibian households reported an improvement in health since getting electricity. The diffusion of electrical appliances can contribute to improve people's health status through:

- the use of electric refrigerators, which bring benefits by preserving food and drinks from external contamination and sustaining the qualities of food longer (Kirubi et al. 2009) (*Electricity demand → Food-preservation devices → People's health* in Figure 6);
- electric lighting that can reduce household air pollution and associated lung disease and eye problems, as well as and burns and poisonings caused by the use of kerosene (Alazraki and Haselip 2007; Gurung et al. 2011; Brass et al. 2012; Aklin et al. 2015; Grimm et al. 2017) (*Electricity demand → Traditional sources of energy → People's health*);
- access to clean and safe groundwater, which can help reduce health diseases (e.g. typhoid, diarrhoea, parasitic infections (World Health Organization 2003)) associated with contaminated sources of water (*e.g.* surface water) (Somashekhar et al. 2000; Cabraal et al. 2005; Bastakoti 2006; Sovacool et al. 2013) (*Electricity demand → Water pumping devices → People's health*).

Secondly, as a consequence of more income and free time following electricity use, people are reported to care more for their health (Sovacool et al. 2013) (*Electricity demand → Free-time → People's health*). Indirectly linked to electricity, complementary activities that support the realization of sanitary facilities reduce the risk of infective and bacterial disease (Gurung et al. 2011) (*sanitary facilities → People's health*).

At *work* level, Bastakoti (Bastakoti 2006) reports that electrification of energy intensive IGAs led to a cleaner and more healthy operating environment in rural Nepalese villages, especially by reducing the health effects caused by the operation of diesel generators, including polluting fumes and irritation caused by grease and fuel on the body (*Electricity demand → Work security → People's health*). Similarly, Kooijman-van Dijk and Clancy (Kooijman-van Dijk and Clancy 2010) indicate that the use of electric machines are characterized by lower noise levels, dust and smoke and contributed to guaranteeing a healthier and less stressful working environment in rural Bolivia, Tanzania and Vietnam.

At *hospital* level – *viz.* local dispensaries, health centres and hospitals – access to electricity is reported to considerably improve the quality and quantity of medical services offered to local people (*Electricity demand → Health centres electric devices → Medical services → Quality of medical service*). Firstly, refrigeration facilities allow for storing medications, vaccines and blood (Habtetsion and Tsighe 2002; Cabraal et al. 2005; Brass et al. 2012; Aglina et al. 2016; Lenz et al. 2017), and modern machines are used in a variety of medical examinations and treatments, such as laboratory examinations, X-ray analyses (Bastakoti 2006) and surgical machines (Brass et al. 2012). Moreover, when on-grid or off-grid electricity-access replaces or reduce the use of diesel, kerosene and LPG for running appliances and machineries, hospitals might experience high energy cost savings (Lenz et al. 2017). In this context, the literature specifies that the diffusion and installation of new electric equipment is highly dependent on the possibility of local health centres to afford them (Peters et al. 2009) (*Hospital financial liquidity → Electricity demand*) and the reliability of power supply (Brass et al. 2012) (*Power unreliability → Electricity demand*), suggesting the importance of giving *financial support* to local hospitals and guaranteeing an *appropriate O&M of power systems*. Secondly, electric lighting can highly contribute to improve medical services by extending operating hours at night (Gustavsson 2007b; Moharil and Kulkarni 2009; Aglina et al. 2016) and increasing security during surgeries and childbirths (Cabraal et al. 2005) (*Electric demand → Health centres electric devices → Safety → Quality of medical service*). Thirdly, improved communication increases the possibility for health centres to provide people with more information about health-care, prevention of diseases, and to retrieve clients information (Cabraal et al. 2005; Aglina et al. 2016) (*Electricity demand → Health centres electric devices → Health-care related knowledge → People's health*), as well as attract more qualified and trained staff (Cabraal et al. 2005; Lenz et al. 2017).

The improvements of people's health status and medical services can result in a positive feedback on electricity use. An improved health status reduces the need to frequently spend time being sick and money for health service, therefore it preserves households' financial capacity and allows for free-time to dedicate to other activities (*People's health → Free-time* and *People's health → Health-care related expenditures*), but at the same time it reduces the *People turnout at local health centres*. On the other hand, the potential improvement of local medical services can positively impact on households' access to financial capital and time as well, as in rural Nepal (Bastakoti 2006) where people experienced lower cost and need to travel to cities nearby for health care (*Quality of medical service → People turnout at local health centres* that reduces *Long travels for medical treatment* and then increase *Free-time;* and *Quality of medical service → People turnout at local health centres* that reduces *Long travels for medical treatment* and *Health-care related expenditures*). This in turn can benefit local hospitals that experience a higher patient turnover and larger financial inflows (that can be invested in new machines and installed electric load) (*People turnout at local health centres → Hospital revenues → Hospital financial liquidity → Electricity demand*). As explained in sub-sections 2.1.1 and 2.1.3, an increase in people's access to financial capital given by reduced costs for health care can have a positive feedback on electricity demand (a reduction in *Health-care related expenditures* supports the positive *Access to financial capital → Electricity demand* feedback), while more time being healthy can increase the time spent on economically productive activities, sometimes the creation of new IGAs, and subsequently an increase in electricity demand (*People's health → Free-time → Electricity demand*).

The literature suggests that improvements in local health-care can have a direct positive impact on some dynamics that influence levels of population growth. Cabraal et al. (Cabraal et al. 2005) refer to a study carried out in rural Bangladesh in 2003, which reports an infant mortality rate of 4.27% in electrified households, compared to 5.38% and 5.78% in non-electrified households in electrified villages and non-electrified villages respectively. Brass et al. (Brass et al. 2012) suggest that improved medical centres can reduce maternal mortality rates (*Safety → Mortality rate → Local population*). Apart from having a positive impact on the health of mothers and children, electricity can positively impact on population growth locally by changing the in- and out-migration to areas (*Rural-to-urban migration rate → Local population*): Neelsen and Peters (Neelsen and Peters 2011) point out that electrification contributed to the expansion of a southern Ugandan village, which in turn boosted market demand and profits for local IGAs (*Local population → Market demand*). Similarly, others (Kanagawa and Nakata 2008; Gurung et al. 2011) report a business in-migration of people who moved in to electrified villages – in Nepal and India respectively – in order to achieve higher levels of income, while Jacobson (Jacobson 2007) suggests a long-term reduction in rural-to-urban migration when rural electrification is followed by local economic growth and positive effects on education. Dinkelman (Dinkelman 2011) suggests that rural electrification in South Africa impacted rural labour markets by reducing the outflow of individuals from rural areas. On the other hand, improvements in socio-economic conditions attributable to electrification might reduce household size, as Ranganathan and Ramanayya report for electrified households in rural Uttar Pradesh (Ranganathan and Ramanayya 1998), by reducing the fertility-rate (*Electricity demand → Access to financial capital → Fertility rate → Local population*).

As a direct feedback on electricity consumption, an increase in local population is followed by an increase in the number of electricity connections and total electricity demand (*Local population → Electricity connections → Electricity demand*). Secondly, it can cause a potential increase in local market demand with a positive impact on creation of IGAs and business productivity, which in turn generate a growth in electricity demand (see sub-section 2.1.2) (*Local population → Market demand → Access to financial capital → Electricity demand*).

Figure 6 shows these nexus causalities between electricity demand and local health and population.

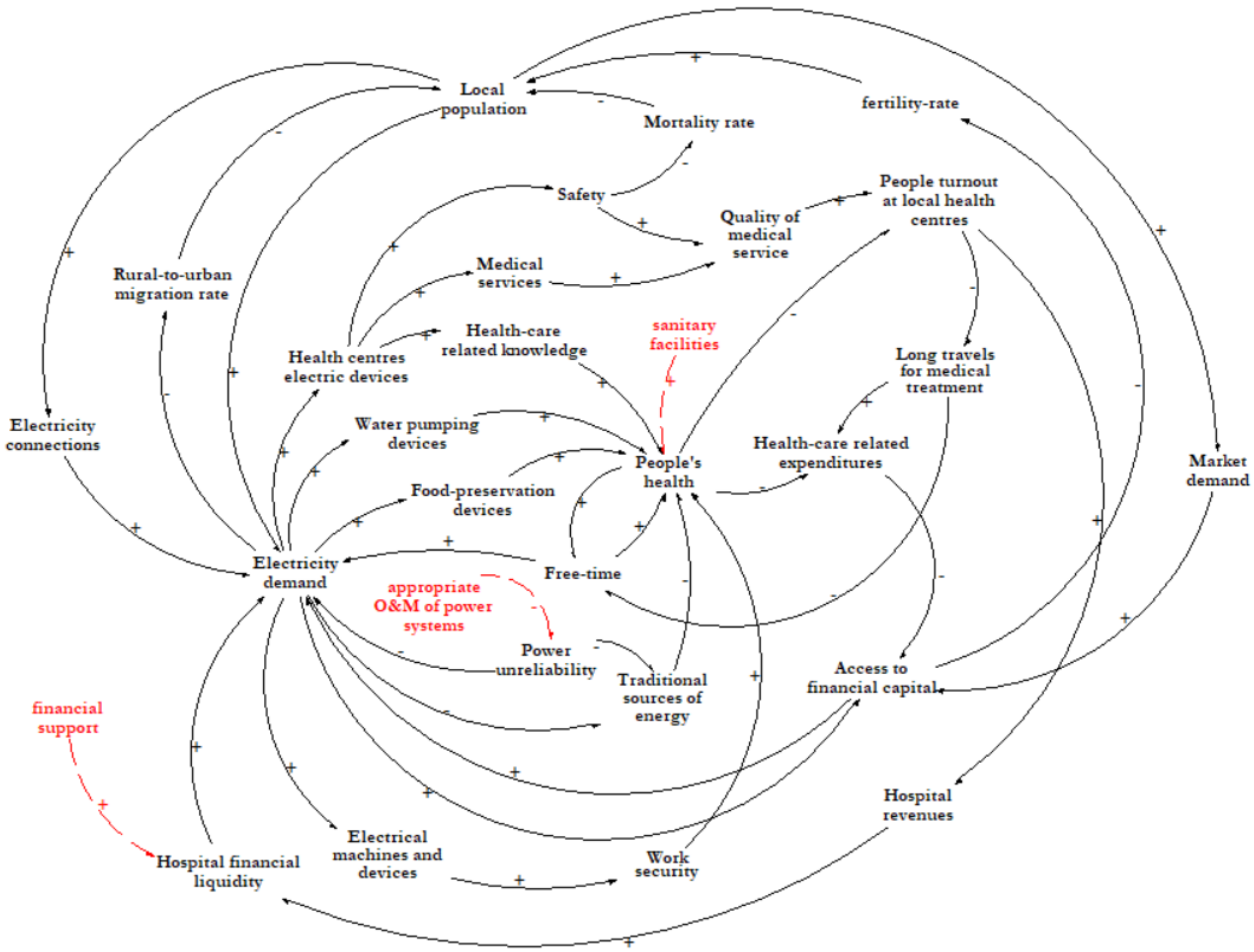

Figure 6. Causal-loop diagram representing the dynamics between electricity demand and local health and population.

2.2.2. Education

The impact of access to electricity on education is a widely-discussed topic in the literature. We cover this nexus by first reviewing studies that state a positive impact of electricity use on people's level of education (without explaining the relation). We report on correlations that seem to support the beneficial impact of electricity use, while being aware of the multiple socio-economic factors that might impact on educational levels of rural people, the reverse causalities, and the potential biases in these results. We then review studies that explain how electricity use in schools and houses may allow people to attain higher school grades and levels, and an improved level of informal education. We finally discuss some possible feedbacks of higher educational attainments on electricity consumption.

From a general point of view, the use of electricity seems to be associated with improved educational standards of people (Alam et al. 1998), also in poor countries (Wolde-Rufael 2005), as reported in Table 4.

Table 4. Examples of impact of electricity use on education.

Reference	Mentioned impact of electricity use on education
Nakata and Kanagawa (Kanagawa and Nakata 2008)	In rural areas of Assam, India, data indicate that a 1-point increase in the percentage of households electrified result in 0.17-point improvement in the percentage of literate people older than 6 years. Also, it is suggested that domestic electricity consumption per capita has a positive correlation with educational attainment, indicating that those households with very low initial levels of electricity consumption can achieve high educational benefits from increasing their consumption of electricity. Further, the literacy rate of Assam state is estimated to rise from 63.3% to 74.4% if all the rural areas were to be electrified, other factors being equal.
Aglina et al. (Aglina et al. 2016)	An increase in electricity access is correlated with an improved literacy rate in the Economic Community of West African States (ECOWAS), though countries with low national electrification rates, such as Cote d′ Ivoire and Mali, have better literacy rates than Ghana that scores higher in both urban and rural electrification rate, indicating the influence of other factors.
Ranganathan and Ramanayya (Ranganathan and Ramanayya 1998)	The increase in literacy rate that occurred in Uttar Pradesh and Madhya Pradesh during the period 1991-1997 is, respectively, nearly half and two-thirds attributable to electrification.
Grogan and Sadanand (Grogan and Sadanand 2013)	Rural Nicaraguan men and women are more than twice as likely to have completed primary education if they live in households with access to electricity.
Sovacool et al. (Sovacool et al. 2013)	The communities that embraced the Multifunctional Platform (MFP) energy program[2] in Mali revealed lower drop-out rates, higher test scores, and higher proportions of girls entering school. A possible reason might be the time freed-up by electricity use (see sub-Section 2.1.1) (Mulder and Tembe 2008), which contributes to decreased irregular attendance (Aglina et al. 2016) and improved marks at school (Gustavsson 2007a).
Dinkelman (Dinkelman 2011)	Electrified rural areas in South Africa have higher fractions of adults with a high school-degree, compared to non-electrified communities
Gurung et al. (Gurung et al. 2011)	Increase in informal education among women in the electrified Tangting village, Nepal
Khandker et al. (Khandker et al. 2013)	An econometric model applied to 42 Vietnamese communes indicates that household electricity connection is correlated with a 9% higher school-enrolment rates for girls and 6.3% for boys.

At *school*, the use of electric lighting might benefit students by extending study hours (Aglina et al. 2016) (*Electricity demand → Study time at school* in Figure 7) and by allowing evening (Gustavsson 2007a) or early morning classes (Alazraki and Haselip 2007) (*Electricity demand →*

[2] "a government managed, multilaterally sponsored energy program that distributed a small diesel engine attached to a variety of end-use equipment" ((Sovacool et al. 2013) pg. 115).

Evening and morning classes). Peters et al. (Peters et al. 2009) find that in rural Benin, electric lighting and the provision of evening classes allow students to work on family business and do housework during the day, contributing to the household economy (*Evening and morning classes → Daily-time for work → Average income*). Electricity availability allows the use of new devices like computers (Bastakoti 2006; Alazraki and Haselip 2007), audio-tapes (Bastakoti 2006), TVs and radios (Alazraki and Haselip 2007; Brass et al. 2012) for educational purposes, and fans for creating a more comfortable environment for all students, finally enhancing the teaching and learning quality (Alazraki and Haselip 2007), as well as the recruitment and hiring of teachers (Aglina et al. 2016) (*Electricity demand → Quality of education* and *Electricity demand → Teacher attraction → Quality of education*). In this context, the availability of funds for schools is pivotal for improving equipment and installed load, as confirmed by Bastakoti (Bastakoti 2006), who reported the diffusion of modern devices especially in private schools. In this regard, electricity might support schools in generating new income to allocate to educational improvements. In Zimbabwe, a rural school started a milling service and generated new income (Mapako and Prasad 2007) – it generates the reinforcing *Electricity demand → school IGAs → school financial availability → Electricity demand* loop. To summarize, these effects contribute to increasing children and adults' *school enrolment*, attendance of classes and grades achievements (Dinkelman 2011; Gurung et al. 2011; Sovacool et al. 2013), i.e. *Education attainments*.

Since electricity use has been found to enhance socio-economic status of rural households, there is also an indirect effect of electrification on school enrolment. Smits and Huisman's work (Huisman and Smits 2009) demonstrate, through a multilevel logistic regression analysis applied to 30 developing countries, that an increase in the level of household's wealth, parents' occupation (especially the father), and education has a positive impact on primary school enrolment of children (*Electricity demand → Average income → Education attainments*). Similarly, Al-Zboun and Neacşu (Al-zboun and Neacşu 2015) interviewed more than 2000 principals and directors of public schools in Jordan, and found that a lack of opportunities, low economic level of households, low quality of educational infrastructures, and low cultural level of parents were pivotal factors affecting the non-enrolment of children in primary schools. This suggests that complementary activities to support community awareness of educational benefits might enhance enrolment (*educational benefits awareness campaigns → School enrolment*). A result that contradicts these findings, is from Lenz et al. (Lenz et al. 2017) who indicate, based on both econometric models and qualitative interviews with teachers, that the probability of rural Rwandan households sending their children to school does not increase as an effect of grid-electrification.

At *home*, many studies mention the increase in evening study hours as the main benefit of electricity on education (Baldwin 1987; Somashekhar et al. 2000; Wamukonya and Davis 2001; Wijayatunga and Attalage 2005; Alazraki and Haselip 2007; Moharil and Kulkarni 2009; Kumar et al. 2009; Gurung et al. 2011; Aklin et al. 2015; Baldwin et al. 2015; Aglina et al. 2016; Mishra and Behera 2016; Grimm et al. 2017; Lenz et al. 2017) (*Evening study time → Education attainments*). Since electricity allows replacing or decreasing fuels use (e.g. kerosene, paraffin, candles) and the related environmental and economic drawbacks (Cabraal et al. 2005), Gustavsson and Ellegård (Gustavsson and Ellegård 2004) report that children study at night in 89% of households with a solar home system, compared to 42% of non-electrified households, where children complain about smearing eyes, lack of candles or paraffin and too weak light (*Electricity demand → Electrical lighting* decreases *Traditional sources of energy's drawbacks* and then increases *Evening study time*. Gurung et al. (Gurung et al. 2011) indicate an increase of reading hours for students after electrification of Tangting village, Nepal, due to a reduction in the use of hazardous traditional lamps. Komatsu et al. (Komatsu et al. 2011) report that the introduction of SHS in Comilla, Kishoreganj, and Manikganj districts in rural Bangladesh allowed children to study in a better environment and to extend their study-time from 8–9 pm until 10–11 pm. Similarly positive results for solar PV based lighting were seen in Ludanzi, Zambia (Gustavsson 2007b) and Gujarat State, India (Agoramoorthy and Hsu 2009).

A part of the literature reports limited or very little positive impact of electricity use on educational attainment. Jacobson (Jacobson 2007) indicates that despite nearly 80% of rural Kenyan households surveyed by the author having school age children, solar lighting was used for studying in only 47% of these homes. Gustavsson (Gustavsson 2007a) reports no evidence of actual improvements of school children's marks as a consequence of access to solar services in the surveyed Eastern Province of Zambia (Gustavsson 2007a). Bastakoti (Bastakoti 2006) and Komatsu (Komatsu et al. 2011) find that in rural western Nepal and Bangladesh respectively, children reported an overindulgence in watching TV that limited their willingness to complete their homework in time (*Electricity demand → Entertainment devices → Evening study time*). In this context, the availability and quality of power supply are two crucial factors (*Power unreliability → Evening study time*). In analysing the social changes in Kenya achieved with solar electrification, Jacobson (Jacobson 2007) suggests that children in households with a larger PV system are much more likely to have access to electric light for studying than children in households with smaller systems. Gustavsson and Ellegård (Gustavsson and Ellegård 2004) also report that children complained about black-outs and restrictions in the use of the power as crucial limiting factors for evening study.

Improving educational attainment can generate positive feedbacks on electricity demand in the long term. Louw et al. (Louw et al. 2008) suggest that education is one of the factors that drives households' fuel choices, as well as the "subsequent energy portfolio used" (p. 2813). Urpelainen and Yoon (Urpelainen and Yoon 2015) conducted a survey among 760 respondents in rural Uttar Pradesh, India, and found that high levels of education increased the willingness to pay for a SHS. Aklin et al. (Aklin et al. 2015) derive econometrically the relation between household's educational level (*viz.* average years of education) and both electrification status (*viz.* if a household has access to electricity or not) and daily hours of electricity for Indian households living in slums, urban and rural areas. They find that more educated households have more need for electric assets and may be more willing to pay for a connection (*Education attainments → Connection rate → Electricity demand*). Similarly, Bensch et al. (Bensch et al. 2011) estimate a probit-regression model to determine that the variable "years of education of household head" is positively correlated at 1% significance level with connection status in Rwanda. On the contrary, Kandpal and Kobayakawa (Kobayakawa and Kandpal 2014) find that in Kaylapara village, Sagar Island of West Bengal (India), the mean class completed by the family head does not show significant difference between households with and without connection to the micro-grid. Rao and Ummel (Rao and Ummel 2017) evaluate the marginal change in the probability to own a refrigerator, a washing machine and a TV in India, South Africa and Brazil in relation to head-of-household's years of schooling, suggesting that more educated households are more willing to adopt new technologies (*Education attainments → Willingness to adopt → Electricity to adopt*). Cabraal et al. (Cabraal et al. 2005) report empirical evidence from rural India and Peru, where the combined provision of electricity and education has been found to generate a greater effect on households' income than each variable taken separately. As a matter of fact, Kirubi et al. (Kirubi et al. 2009) report the experience of Mpeketoni Polytechnic educational institution in Kenya, which after connection to the grid became an important source of technical know-how and skills for youths who then found employment in local IGAs, generating a time-delayed feedback between *Educational attainment* and *Average income* (marked with two dashes in Figure 7). Khandker et al. (Khandker et al. 2013) suggest that higher educational benefits achieved by rural Vietnamese children as an effect of electrification might have resulted in higher and more productive employment levels. In his econometric study, Rao (Rao 2013) found that the years of education of household' head is a positive determinant of income for Indian NFEs. Since households' income and financial availability have been found to be pivotal drivers of electricity use, all these studies confirm that improving peoples' educational attainments can positively impact future electricity consumption (*Education attainments → Average income → Electricity demand*).

Figure 7 reports the diagram of nexus causalities between electricity demand and educational attainment. The mark on the causal link, which connects *educational attainment* and *average income*, indicates a time-delay in the occurrence of the represented feedback as evident from the literature. We also highlight the importance of combining electrification activities with awareness campaigns regarding the benefits of education, programmes of financial support to local schools (*financial support → school financial availability*), and correct O&M of the power systems (*appropriate O&M of power system → Power unreliability*).

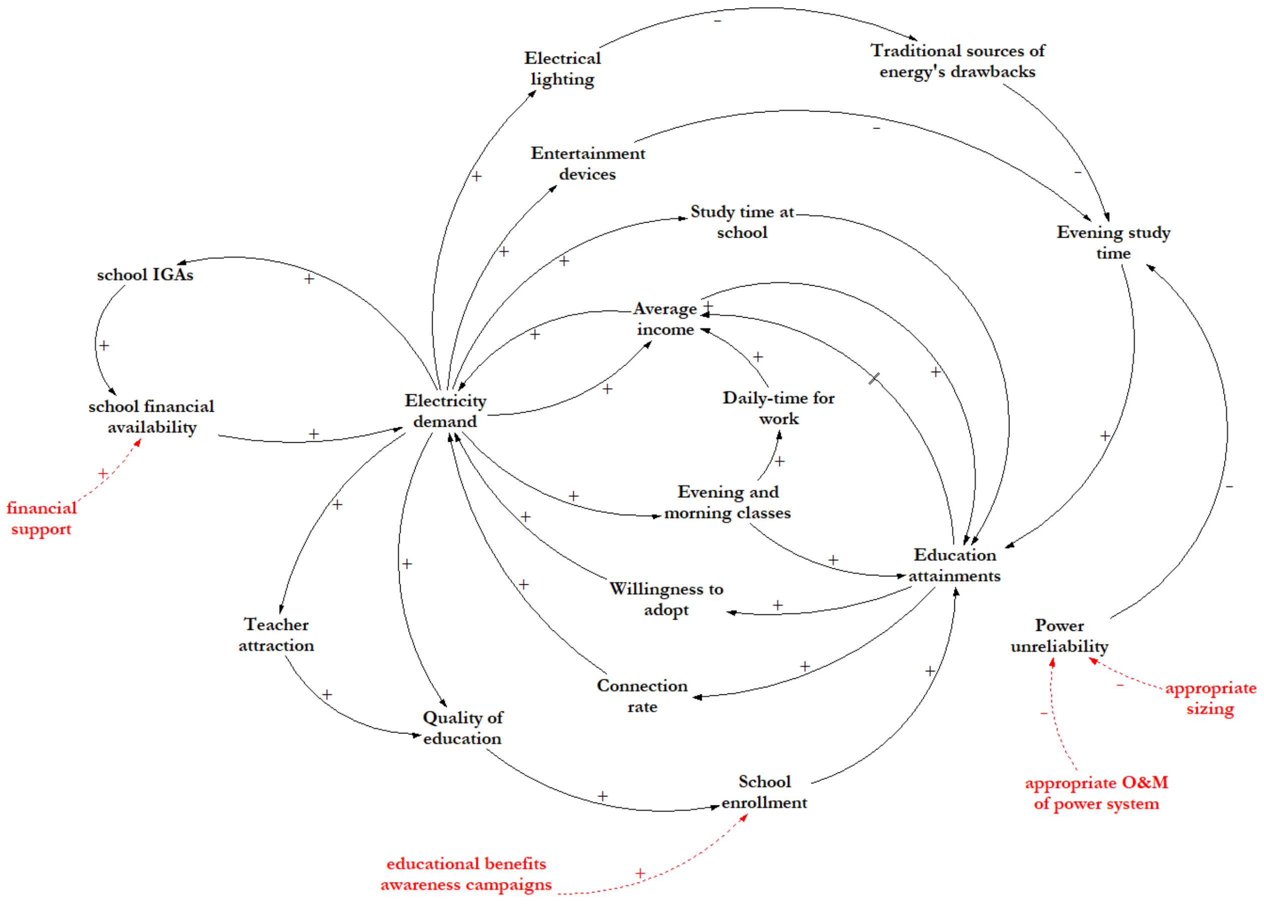

Figure 7. Causal-loop diagram representing the dynamics between electricity demand and education.

2.2.3. Habits and social networks

In terms of changes in people's daily habits and activity scheduling, the availability of electrical lighting can contribute to extending the length of people's active day (*Electricity demand → Electrical lighting → Daily-time extension* in Figure 8). Matinga and Annegam (Matinga and Annegarn 2013) report that the provision of access to electricity in Tsilitwa village, South Africa, allowed household members to wake up earlier, about half-hour before sun-rise, and go to bed about 2-3 hours later. Similarly, Roy (Roy 2000) indicates that the lighting hours in households provided with solar lanterns in a rural Indian village went up from 2 hours to 4 on average (and up to 6 hours in some cases). Lenz et al. (Lenz et al. 2017) state that in rural Rwanda, "the availability of electricity in the communities clearly had a significant effect on the daily routine of all household members" (p. 99), since it extended the day by 50 minutes on average. On the contrary, Grimm et al. (Grimm et al. 2017) did not find statistically significant changes in the time spent on daily and evening domestic labour between electrified and non-electrified rural households in Rwanda. In addition to this daily time extension, the literature reports that access to electricity can facilitate household activities by decreasing the burden of work and time. Kumar (Kumar et al. 2009) reports that in 5 centres in Sagar Dweep Island in India, 38% of households stated a benefit from time savings for cooking (*Electricity demand → Efficiency (completion rate) of housework → Daily burden of housework*), while 17% indicated having more time for household work at night (*Evening housework → Daily burden of housework*). More time available for women's household work at night has been reported also by others (Agoramoorthy and Hsu 2009; Moharil and Kulkarni 2009). Obviously, the diffusion of TVs and entertainment devices might reduce time dedicated to housework (*Electricity demand → Entertainment devices → Evening housework*). Bastakoti (Bastakoti 2006) indicates that the use of electric water pumps in rural Nepal allowed people to reduce time for collecting water from 7-8 hours per day initially to 1/2 hour per family, increasing available time for farming and leisure activities. Also Grogan and Sadanand (Grogan and Sadanand 2013) report a decrease in time for fetching water (and firewood) in Nicaragua. Komatsu et al. (Komatsu et al. 2011) report that households owning a SHS in rural Bangladesh spend less time for recharging car batteries at recharge stations, experiencing less burdens (*viz.* heavy weights to carry), and more free time (saving at least 40 minutes for the round trip on average plus the recharging time for batteries).

According to Grogan and Sadanand (Grogan and Sadanand 2013) in Nicaragua, "electrification, particularly for poor people, may be more about the extension of the working day than about labour-saving appliances" (p. 253). In this context, time freed-up by electricity can be devoted to productive activities and it has been found to have a positive effect on people's propensity to start a new IGA, with a consequent feedback on electricity demand (sub-section 2.1.1 and 2.1.2) (*Daily burden of housework → Free-time → Average income → Electricity demand*). Grogan and Sadanand (Grogan and Sadanand 2013) suggest that the daily time spent by rural Nicaraguan women living in electrified households in salaried work can be three times as much as the time spent by women living in unelectrified households. Similarly, they report that men living in households with access to electricity decreased by half their time spent in family agriculture and doubled the time spent in non-agricultural activities. On the contrary, Lenz et al. (Lenz et al. 2017) do not observe a change in income generation patterns as an effect of free-time in electrified Rwandan households. More available free-time seems to increase time dedicated to reading and cultural activities (Gustavsson 2004; Bastakoti 2006; Gurung et al. 2011), which may potentially benefit people's educational attainments and all the consequent feedbacks that has on electricity use (*Free-time → Education attainments → Electricity demand*). However, Sovacool et al. (Sovacool et al. 2013) highlight that people are sometimes unable to capitalize on the free time created, suggesting the need to implement parallel educational activities and capacity building (*educational awareness activities → Education attainments* and *capacity building → Average income*).

The evolution of electricity demand can impact the social structure and network of electrified communities (Baldwin et al. 2015). In Tsilitwa village, South Africa, Matinga and Annegam report that differences in household electrical appliances intensified the feelings of exclusion and inequality, highlighting that "electrical appliances displayed in houses of the better-off represent a world from which they [poorest families] felt excluded" ((Matinga and Annegarn 2013), pg. 295), pushing people into changes in aspirations and spending (*Electricity demand → People aspirations → Average market expenditures*). However, this reinforcing feedback is sometimes hindered by the local social habits, traditions, gender relations and culture that can negatively influence people's aspirations and investment decisions, such as people in Zanzibar having food preferences for traditionally prepared food over use of electric cookstoves, or male control over money and technology, limiting women's abilities to purchase household equipment (Winther 2008). Rahman and Ahmad (Rahman and Ahmad 2013) observe that the diffusion of SHS in rural Bangladesh brought mostly recreational and leisure benefits. Bastakoti (Bastakoti 2006) indicates that the possession of a television is considered a luxury and status symbol in rural South Africa. On the other hand, the same author suggests that families without cable frequently go to their richer neighbours' homes to watch TV, increasing households' meetings and time together (*Electricity demand → Entertainment devices → Social connectivity*). Komatsu (Komatsu et al. 2011) and Lenz et al. (Lenz et al. 2017) report the same dynamics also for rural Bangladeshi and Rwandan households respectively. Similarly, Gustavsson and Ellegård (Gustavsson and Ellegård 2004) report that children living in villages located in the district of Nyimba, Zambia, gathered together in one of the houses with a SHS to study. Lighting and the related perceived improved security, as well as evening market operation, seem to increase outdoor and/or indoor evening meetings and chats, and connectivity among people (Gustavsson 2004; Alazraki and Haselip 2007; Shackleton et al. 2009; Kooijman-van Dijk and Clancy 2010; Matinga and Annegarn 2013) (*Electricity demand → Electrical lighting → Social connectivity*). Even within the same household, Wijayatunga et al. (Wijayatunga and Attalage 2005) report that 68% of surveyed households in Badulla district, Sri Lanka, claimed to benefit from having more time together through activities such as watching television while having dinner.

Electrification allowed enhanced access to information (Kooijman-van Dijk and Clancy 2010), communication and connectivity even outside local communities (Baldwin et al. 2015) (*Electricity demand → Communication devices*). Jacobson (Jacobson 2007) report that rural electrification in Kenya facilitated rural–urban communication through the diffusion of television, radio, and cellular telephone charging, increasing rural–urban connectivity, especially for the rural elite and middle class. Similarly, Rwandan households interviewed by Lenz et al. (Lenz et al. 2017) indicated that mobile phones are especially used for calling people who live outside the province. Gustavsson (Gustavsson 2007a) suggests that children and adults in rural Zambia experienced more access to news and events taking place outside the rural community through radio and TV broadcasts.

In accordance to the theory of innovation diffusion (Bass 1969; Peres et al. 2010), enhancing connectivity and social networks increase the process of word of mouth, acceptability of new products, and related probability to become an adopter, enhancing the diffusion of electrical products and its feedback on the evolution of electricity demand (*Social connectivity → Word of mouth (social connectivity) → Electricity demand*). In this context, local government officials or heads of the villages can play the role of "influentials" (Van den Bulte and Joshi 2007; Goldenberg et al. 2009; Urmee and Md 2016) in bringing electricity to their communities and enhancing the diffusion of electrical devices (Kooijman-van Dijk and Clancy 2010). Since the use of television and radio might facilitate the ability of business advertisers to reach a wider audience (Jacobson 2007) and increase local demand for goods and services, local shops and retailers can experience higher trades and revenues, with related feedbacks on electricity use, as discussed in sub-section 2.1.1 and 2.1.2 (*Communication devices → Advertisement → Market demand → Electricity demand*).

Figure 8 reports the diagram of nexus causalities between electricity demand, habits and social networks.

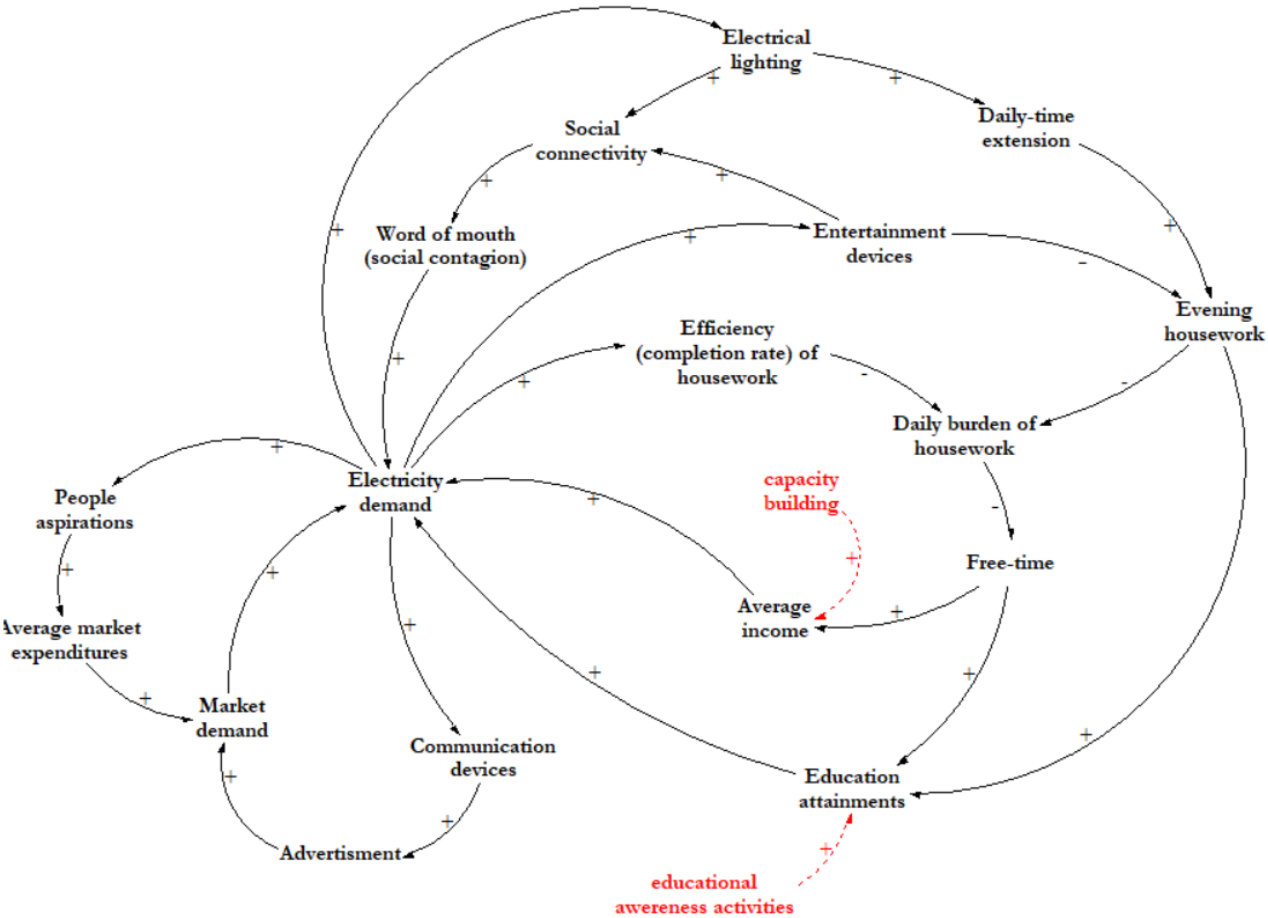

Figure 8. Causal-loop diagram representing the dynamics between electricity demand, habits, and social networks.

3. Insights from literature for energy modelling

In this section, we discuss the implications of our findings from an energy modelling perspective. We discuss how the conceptualized variables, feedbacks and causal diagrams can be useful to understand the complexities in the energy-development nexus and to formulate possible appropriate energy models. Our review confirms that the energy-development nexus is complex. As such, the behaviour/outcome of the nexus cannot be intuitively understood (Forrester 1971). In order to improve understanding of complex systems, a number of computer aided modelling methods have been developed over the last decades, e.g. agent based modelling, system dynamics, neural networks, and operational research. With the usage of these tools and methods, complex problems can be analysed and tested in computer environments in order to improve understanding of the studied systems.

Through the use of causal diagrams, this paper has presented a conceptualization of factors and processes found in the energy-development nexus (see Figure 3 to Figure 8). Causal diagrams are similar to the causal loop diagrams used in system dynamics modelling methods. In system dynamics, causal loop diagrams are commonly used for formulating a problem through a dynamic hypothesis, for communicating a model (Morecroft 1982), and for making qualitative analysis of complex systems (Wolstenholme and Coyle 1984). Even though conceptual models are often used as intermediate steps towards simulation models (Robinson 2008), important insights can be drawn from qualitatively analysing conceptual models (Wolstenholme and Coyle 1984). A few of the factors in the energy-development nexus were identified to be exogenous, but the main part of the diagram depicts the relationship of the factors through closed causal loops. The causal loop diagrams show how factors identified in the energy-development nexus literature are interconnected, thereby improving our understanding of the energy-development nexus. This results in two insights:

(i) As factors are largely interconnected, it is not suitable to use reductionist methods to analyse the energy-development nexus: e.g. the relationship cannot be sufficiently studied using only a limited set of factors without having knowledge of the full contextual setting. Instead a systems-thinking approach that includes the full complexity is needed and advised.

(ii) Many of the identified factors are connected through feedback loops. In order to identify the system's behaviour and to capture the dynamics in the energy-development nexus, a simulation approach that takes feedbacks into account is needed.

The initial methods or procedure in developing many models consists of a process of identifying factors and processes that are important for the considered problem, as we did in the Section 1. A process of formulation of a *simulation model* follows. This part consists of formulating factors into variables and formulating the explicit mathematical relationships between variables. In terms of modelling complex systems, the identification of factors and processes is a substantial part of the modelling work load. Even though there are several tools (Luna-Reyes and Andersen 2003) available to help modellers and scientists to identify and assign variables and parameters in models, the process of quantification is inherently problematic when dealing with social science problems. This is evident from the limited extent this has been done in existing studies dealing with the energy-development nexus. A cause of concern is that studies often analyse a specific relationship or assume a direct relationship between highly aggregated indicators and thereby rely on a range of assumptions, often implicitly. This results in a wide range of numbers, often with low or no statistical confidence, which can seem contradicting or unusual. However, reported quantitative estimates from literature can still be useful in the simulation process. Using methods of parameter estimation and condition tests, the ranges reported in literature can be used to build confidence in a simulation model. One tool to handle variable and parameter uncertainty is the use of Monte Carlo simulation to investigate the relationship between parameter space and behaviour space (Pruyt and Islam 2015). This allows the modeller to relate behaviour modes with parameter ranges to improve model confidence. In addition, this allows the modeller to use the model as a learning tool and improve the understanding of the energy-development nexus, e.g. by simulating the impact of the exogenous variables represented at the tail of the dashed lines (Figure 3 to Figure 8) in the dynamics under study. However, in order to make such tests realistic, they need to rely on some knowledge of contextual factors.

In addition, the lack of access to data when working in rural areas in developing countries adds further difficulties to the simulation process. Access to time-series data for statistical analysis is considered important in system dynamics for model calibration (Sterman 2000). Therefore, if long-term data sets are not available, alternatives to deal with stochastic uncertainties need to be considered. We want to emphasize that we consider long-term time series to be important both in model development and validation, and that lack of time-series data can never be substituted. However, we do not consider the lack of time-series data to be a sufficient problem for not considering a system dynamics approach. Even though high-quality long time-series are not common when working in rural areas in developing countries, high-quality qualitative data can often be obtained through case studies and structured interviews. As local residents often have a plethora of practical knowledge and 'know-how', even though they lack precision, they can be good sources for retrieving estimates on reference modes and historical trends.

Conclusion

Around the world, more than a billion people do not have reliable access to electricity. This is considered a limiting factor to the socio-economic development of, especially, rural communities. During the last decades, international donors, organizations, NGOs, universities, energy planners, practitioners, and private companies have been investing a lot or resources in programmes and projects that aim at improving people's socio-economic conditions through access to energy. Despite these investments, the scientific literature reports only fragmentary and sometimes contrasting results regarding impacts, and methodological inconsistencies limit the comparability and generalisability of results. It is, however, not just a question of undertaking statistical comparative studies. Existing literature shows that the electricity access-development nexus is very context- and time-specific, with high complexity and emergent dynamics. Hence, the application of linear or pre-defined sets of relations of cause and effect necessarily fail to accurately describe, or predict, the impacts with any level of precision that such results are useful for planning and making electricity provision work in practice, at the local level.

In the context of rural electricity planning, the limited knowledge of the impact of electricity access on local socio-economic development and the consequent feedback on electricity demand can negatively impact on the sizing process of energy systems, especially the off-grid ones. Therefore, being able to understand and model the aspects and dynamics that determine rural electricity use can lead to more robust energy planning solutions in rural areas. With our work, we therefore analyse the dynamic complexities related to the impact of electricity access and consumption on rural socio-economic development, and vice versa, and we develop graphical representation of the multiple existing causal relations of the issue. Our final goal is to enhance a better understanding of the electricity-development nexus, as well as to derive insights and useful guidelines for developing appropriate models capable of incorporating and simulating such complex relations.

Our results confirm that the energy-development nexus is complex to an extent that it can be usefully described as a 'complex system'. Electricity use is interconnected through complex causal relations with multiple dimensions of socio-economic development: *income generating activities, market production and revenues, household's economy, local health and population, education, and habits and social networks*. We find that focusing on the impact of electricity use for only a unique or isolated set of socio-economic aspects provides a limited and incomplete view of the issue. Indeed, our causal diagrams suggest that the electricity-development nexus should, if possible, be investigated as a whole, since all the dimensions are interconnected, and positive dynamics on one side can create negative feedbacks on the other. In this context, the nexus between electricity use and each socio-economic dimension generates positive dynamics only when complementary activities are considered (e.g. capacity building, awareness campaigns, access to credit, etc.) and infrastructural preconditions are guaranteed (e.g. asphalted roads, reliability of the electric network, etc.).

From a modelling perspective, our causal diagrams can be seen as a first step of the *conceptualization* phase of model building, which aims at describing and understanding the structure of a system. The presence of multiple uncertain parameters, strong non-linear phenomena, complex diffusion mechanisms, and time-adjustments of technology perceptions that describe the complex system under analysis suggest that systems-dynamic *simulations* can allow dealing with the high uncertainties at stake, especially when coupled with stochastic approaches such as Monte Carlo simulations and qualitative data eliciting techniques. However, we stress the need to calibrate and validate models when historical data are present. Adequate data and calibration are recurrent issues when dealing with electricity-development issues. Indeed, we finally encourage all practitioners and the scientific community involved in rural electrification studies to intensify efforts towards reliable data collection and publishing.

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