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RESEARCH PAPER

WILEY Systems *and* Behavioral Research Science

Tackling complexity and problem formulation in rural electrification through conceptual modelling in system dynamics

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Funding information
Adlerbertska Stiftelserna; Svenska Forskningsrådet Formas

Abstract

Mini-grids are considered important in order to improve access to electricity in developing countries. Their technical and organizational independence from the large national grids and their interactions with local social, economic, and environmental factors suggests that system dynamics is a useful method of analysis. However, the successful implementation of mini-grids in rural electrification has partly been prevented due to complexity issues, making problem formulation difficult. Most problem-solving methods, such as system dynamics, require well-defined problems. Previous work on the problem formulation process in system dynamics is limited. This work presents a conceptual framework for tackling complexity and uncertainties in rural electrification. The conceptual framework is general and draws on research in conceptual modelling and system dynamics. The focus is on the learning that can be achieved from a system description and how it can be used to tackle complexity by reducing uncertainties and improving knowledge.

KEYWORDS
complexity, conceptual modelling, problem formulation, rural electrification, system dynamics

1 | INTRODUCTION

According to projections by The World Bank and the International Energy Agency, one billion people will receive access to electricity in Africa by 2040 (IEA, 2014; The World Bank, 2017). A majority of these people live in rural areas. There are two predominant tracks in terms of supplying rural areas with electricity in developing countries: grid extension and off-grid systems. Grid extension refers to the process of extending national grids into rural areas. Off-grid refers to the various types of

technologies that does not use the national grid to deliver electricity. It is generally agreed that both grid and off-grid technologies are needed if rural communities are to gain the full benefits of electricity access within the foreseeable future (Ahlborg & Hammar, 2014; Díaz, Arias, Peña, & Sandoval, 2010; Tenenbaum, Greacen, Siyambalapitya, & Knuckles, 2014; Urpelainen, 2014).

One type of off-grid systems is mini-grids. Mini-grids are small independent generation and distribution systems supplying a hundred to a few thousand customers. The diffusion of mini-grid technologies in rural Africa

has until recently been slow and have met a wide variety of problems. The success of mini-grids depends on local social, economic, and environmental conditions. Similarly, local social and economic development and environmental conditions depend on access to reliable, affordable, and renewable electricity, pointing to a feedback between these factors. Access to electricity directly impacts and is in turn impacted by education, health, agriculture, income and expenditures, and infrastructures, resulting in multiple feedback processes. Furthermore, introduction of electricity can reinforce or change existing social, environmental, and economic structures (Ahlborg, 2015). In addition, local context differences and lack of knowledge give rise to uncertainties and sometimes conflicting results from different mini-grid cases. This suggests that knowledge based on single mini-grid cases is not sufficient for obtaining a general understanding of the systems. The many factors, their high interdependency, feedback, and the many uncertainties make rural electrification complex (Beer, 1979; Flood & Carson, 1993; Gigch, 1991).

Complexity is often mentioned by rural electrification and development scholars, that is, Brent and Rogers (2010) described the environment that mini-grid operates in as complex; Blum, Bening, and Schmidt (2015) described mini-grids as complex due to the use of electricity and maintenance of the technology (generation and distribution of electricity) at the local level; and, focusing on the impacts of electricity, Matinga and Annegarn (2013) found paradoxical impacts from electricity and attributed them to the complexity of the social setting in which electricity acts. However, none of the research mentioned have explicitly tackled complexity as an issue in rural electrification. Even though complexity is often mentioned, there has been a lack of systems methods applied in development research (Ramalingam, Jones, Reba, & Young, 2008). The large interdependence between factors makes reductionist methods ineffective and identifying the origin of problems in rural electrification difficult. The lack of considering complexity in developing countries has caused inappropriate problem formulations and ineffective policies (Ryan & Mothibi, 2000).

System dynamics is used to analyse complex problems (Sterman, 2000), and was developed to analyse endogenous problems and generally has had a focus on development of formal (simulation) models. System dynamics allows both for qualitative and quantitative analysis, and a commonly used tool for conceptual modelling in system dynamics is causal loop diagrams. System dynamics focus on tackling specific problems and lack structured methods for eliciting and tackling problem formulation (Lane, 2000). Conceptual modelling tools such as causal loop diagrams have been used as a conceptualization tool in the early phase of system dynamics modelling but relies on an initial understanding of the problem.

In rural electrification, problems involve local contexts (with large variations) and has direct influence on local social, economic, and environmental systems. Problems in rural electrification can therefore be described as organized complex[1] problems according to Weaver (1948). In addition, rural electrification is context-dependent where actors (with different goals) intervene, thus affecting the outcome, suggesting that there is no single specific problem perception or formulation. Rural electrification can therefore be described as "messy" (Ackoff, 1997; Vennix, 1999). Complex and messy systems can behave counterintuitive, which can explain why there have been inconsistent outcomes in rural electrification (Matinga & Annegarn, 2013).

The complexity, many feedback processes and the high interdependency of variables in mini-grids in rural electrification suggest that system dynamics is a useful method for problem solving. However, the complexity and "messiness" are also initial barriers in terms of understanding rural electrification, making problem formulation difficult. A well-defined problem is essential for a successful system dynamics modelling process (Mashayekhi & Ghili, 2012). Previous work on tackling messy problems using system dynamics has been performed by Vennix (1999) and is similar to works by Lane (1992), Wolstenholme (1992), and Eden (1994) on problem structuring. Previous work has been based on management cases in order to solve situational problems and is neither suitable for analysing general dynamics covering multiple cases, the uncertainties nor the mix of different data sources that can be found in rural electrification. In addition, methods such as group model building or interactive system dynamics use conceptual modelling for problem conceptualization, which requires an already identified problematic situation.

In such circumstances can conceptual modelling be used to understand problem situations (Robinson, 2008a), and can therefore aid in the problem formulation process. However, the method developed by Robinson considers general simulation models and is not appropriate for the specific limitations of system dynamics. Specifically, system dynamics is suitable when the investigated problem is characterized by an internal structure

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[1]In *Science and complexity*, Weaver (1948) identifies three types of problems: problems of simplicity, problems of disorganized complexity, and problems of organized complexity. Problems of organized complexity include problems that involve a large number of variables that interacts and whose interactions show features of organization.

consisting of closed feedback loops and delays. In addition, Robinson's work considers conceptual models in general and does not include the limitations of using conceptual modelling tools specific for system dynamics, for example, causal loop diagrams. Thus, the purpose of this paper is to investigate conceptual modelling as a tool for tackling complexity and problem formulation in rural electrification. Specifically, using causal loop diagrams as a conceptual modelling tool in system dynamics, the paper aims at answering the following two questions:

1. Can conceptual modelling be used to tackle the complexity and problem formulation in rural electrification?
2. How can conceptual modelling be utilized to aid in the problem formulation process?

The paper is divided into the following sections. First, a review of conceptual modelling and problem formulation is presented. This is followed by the proposed conceptual framework to tackle complexity and problem formulation. The conceptual framework is then applied in a rural electrification case study in order to aid in the problem formulation process. The paper ends with a concluding discussion.

2 | CONCEPTUAL MODELLING AND PROBLEM FORMULATION

In system dynamics, different conceptual modelling tools have been used in various forms since its beginning (Forrester, 1961). They are often used in two different phases in the modelling process: communicating model structure and describing the reference mode (dynamic hypothesis). One of the most common conceptual modelling tools in system dynamics is causal loop diagrams. Causal loop diagrams can be used to link stock and flow model's behaviour with the model structure (Luna-Reyes, 2003; Morecroft, 1982) and are used in applications of system dynamics when interactions with clients and learning are important, such as group model building (Vennix, 1996) and models for learning (Lane, 1992). In addition, causal loop diagrams in system dynamics can be used during the initial conceptualization of the problem by stating a dynamic hypothesis, for example, before a formal (simulation) model has been developed. The application is then similar to that of Robinson (2008a) and Pace (2000).

Conceptual models can be considered as abstractions and/or simplifications of a real or proposed system (Robinson, 2008a). One of the challenges in conceptual modelling is therefore to make appropriate abstractions,

simplifications, and assumptions of the system under study (Pidd, 2003; Robinson, 2008b). Pace (2000) acknowledge that the processes of formulating simulation requirements and formulating a conceptual model often takes place simultaneously and cannot be separated, thereby suggesting that conceptual models can be tools for identifying simulation requirements. Because simulation requirements include the choice of a relevant boundary and its conditions, it is similar to a problem definition. This implies that the formulation of conceptual models is similar to that of problem formulation. Robinson (2008a) identifies that conceptual modelling involves moving from a problem situation to a definition of what to include in a simulation model and is then similar to works by Vennix (1996) and Lane (1992). However, this also suggests that conceptual modelling requires an initial problem situation and thus also require a level of initial knowledge of the problematic situation. Problem formulation can thus be considered as the process of acquiring sufficient knowledge to identify a problematic situation and then takes place at an earlier modelling phase than the works by Vennix (1996) and Lane (1992).

According to Fishwick (1995), one of the properties of conceptual models is that they often are vague and ambiguous. It is also recognized that conceptual models are mainly qualitative (Heemskerk, Wilson, & Pavao-Zuckerman, 2003; Wolstenholme & Coyle, 1983). Qualitative information is rich in meaning and descriptions but also relates to specific contexts (Miles & Huberman, 1994) and are therefore uncertain and ambiguous when considered in general contexts. However, ambiguity can also be meaningful according to Luna-Reyes (2003), and be an asset during the problem identification phase, when knowledge about the problematic situation is limited. With limited knowledge, it is not possible to make accurate and certain statements, but the descriptive nature of conceptual models can be used to generate insights (Coyle, 2000), identify boundaries, and shed light on the problem context (Kotiadis & Robinson, 2008), and thus aid in problem formulation (Pidd, 2007).

Problem formulation is one of the most important aspects of a successful modelling process (Lyles & Mitroff, 1980; Mashayekhi & Ghili, 2012). Problem formulation in system dynamics is often described as iterative, where the problem is re-evaluated through model development (Sterman, 2000). However, this includes developing and re-evaluating stock and flow models and making quantitative analysis, which requires large amount of resources. Having an initial well-defined problem is therefore of great importance to guide the initial model development and to make the subsequent modelling process efficient.

The issue of problem identification in system dynamics has been relatively unexplored (Mashayekhi & Ghili,

2012). Vennix (1999) discussed how to handle the issue of ill-defined problems in group model building and focused on the skills of the facilitator when interacting with actors. Mashayekhi and Ghili (2012) developed a framework using ambiguity to aid in the problem identification process. In addition, as described by Forrester, diagrams describing system structure can be used to identify new problems (Forrester, 1971), thus serving as a conceptual aid during the problem formulation, but relies on a significant system knowledge. This qualitative nature has been used within interactive system dynamics (Lane, 1999) and group modelling building (Vennix, 1996), where causal loop diagrams can be used to guide model development through discussion, and as such aid during the problem formulation process. However, both interactive system dynamics and group model building relies on elicitation of mental models from actors through interaction and use causal loop diagrams during the problem conceptualization phase, thus requiring knowledge about an existing problem. As such, they do not consider the initial phase in problem formulation, which is characterized by the modellers' lack of knowledge and high uncertainties.

3 | A FRAMEWORK FOR TACKLING COMPLEXITY AND PROBLEM FORMULATION

Drawing on the work by Coyle (2000), Wolstenholme (1982), Wolstenholme and Coyle (1983), Vennix (1996, 1999), Allison and Hobbs (2006), and Robinson (2008a, 2008b), we propose a framework based on conceptual modelling in order to tackle complexity and aid in the problem formulation process. The framework originates from experienced difficulties during the problem formulation process. Specifically, it originates from the lack of direct and detailed knowledge of the system under study and high uncertainties during the early phase of the problem formulation process.

The conceptual framework is shown in Figure 1. The framework describes the development of a problem formulation using conceptual modelling. It establishes three steps within the scope of conceptual modelling, with the purpose of producing an endogenous problem formulation. The problem formulation can then either be used as a basis for a system dynamics simulation process (Sterman, 2000) or qualitative analysis (Wolstenholme & Coyle, 1983). A fundamental assumption in the problem formulation process described in the framework is that an explicit system description can bring insights (Coyle, 2000) and that system description and insights evolve in parallel.
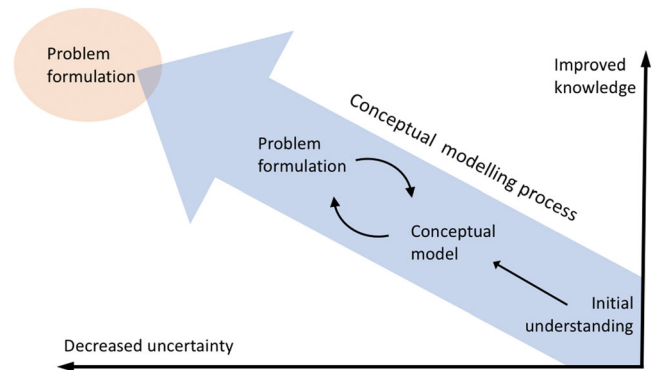
FIGURE 1 Framework for using conceptual modelling to aid in the development of a problem formulation. The framework starts from an initial understanding of the problematic situation and then use conceptual modelling to arrive at a problem formulation. The framework describes the conceptual modelling process in relation to reduction in uncertainties (*x*-axis) and improved knowledge (*y*-axis) [Colour figure can be viewed at wileyonlinelibrary.com]

Step 1 concerns the formulation of an initial understanding. Any modelling attempt rely on an initial understanding of a problematic situation (Allison & Hobbs, 2006). The initial understanding can originate from existing knowledge, from acquiring new knowledge or from both. This includes but is not limited to: research literature, experience, discussions, and access to data. However, in messy situations, knowledge about the problematic situation is limited and is surrounded by uncertainties. As knowledge about the problem is initially low and the problematic situation is surrounded by large uncertainties, it is not possible to establish a satisfactory system understanding.

In order to cope with the lack of knowledge and the uncertainties, it is necessary to first identify some of the relevant elements, for example, entities and causal relationships between system entities and their associated uncertainty. Causal relationship's associated uncertainties are classified based on how "direct" (Petersen, Sinisi, & van der Laan, 2006; Rubin, 2004) the causal relationship is perceived to be and if it deviates from previous knowledge or information from other sources. A causal relationship's "directness" is based on the number of presumed intermediate causal steps and the entities along these steps. With an initial lack of knowledge, the number of intermediate causal steps and their entities is not known, but can likely be estimated as either "many" or "few," thus aiding in classifying their uncertainty. Overall, the high uncertainty and lack of knowledge make problem formulation at this stage difficult.

Step 2 focus on using the initial understanding to develop an initial causal loop diagram. However, formulating causal loop diagrams requires explicitly stating

variables and thus require an association between entities and variables. Entities can be represented by indicators, which are attributes of variables. Which indicators that are relevant representations and attributes depends on the model's purpose. The initial understanding is based on a number of uncertain assumptions and contains a high degree of uncertainty regarding relevant representations (because the purpose is vague). A causal loop diagram at this early stage therefore lacks the rigour and precision of a clearly formulated problem. Furthermore, the uncertainty implies that the causal loop diagram may both include unnecessary variables and relationships and lack variables and relationships that are relevant for a more stringent problem formulation. However, the sketching of a system structure helps the modeller to explicitly state assumptions, and thus require the modeller to evaluate them; identify inconsistencies and gaps amongst entities, with associated variables and relationships; and thus reduce the scope of the problem. Therefore, both the development of the initial conceptual model and the conceptual model itself represents increase in knowledge about the problematic situation.

Another issue during the second step is to handle information originating from different sources. It is likely that various sources use different vocabularies and therefore the identification of entities, indicators/variables, and relationships may contain uncertainties. Nonetheless, because conceptual models can be ambiguous, the differences can be an asset in order to develop a causal loop diagram (Fishwick, 1995; Luna-Reyes, 2003). In order to aid in this process, we propose to combine entities with their associated variables (and their associated casual relationships) based on their perceived similarity and containment.[2] For example, if two variables seem to be related or similar (such as, e.g., disposable income and income), with one belonging to a subset of the other, the second variable can be used as a proxy for both (e.g., we may substitute disposable income with income). This process of merging variables reduces detail and therefore also information, but it also increases the relevance of variables and relationships and the usefulness of the causal loop diagram. The relevance of variables and relationships and the usefulness of the causal loop diagram relates to the purpose of the model, which is initially vague (because there is no clear problem formulation). Improving the relevance and usefulness of variables and causal relationships are considered an essential aspect of developing an initial casual loop diagram and reducing the problem scope.

The aim of the third step is to formulate a problem expressed in the structure of the entities, relationships, and variables/indicators. This is done through an iterative process of re-evaluating the causal loop diagram and its entities and relationships. The purpose of the re-evaluation is threefold: to clarify and re-examine the assumptions and the knowledge on which the causal loop diagram is built, thus reducing the uncertainty; reduce the number of entities and associated variables and causal relationships ambiguity or increasing their relevance; and to identify missing entities, with associated variables and causal relationships.

A necessity for identifying missing variables and causal relationships and improve their relevance is that the model's purpose needs to be specified. The causal loop diagram based on the initial understanding can in this context be used to guide the problem formulation process by guiding discussions (Coyle, 2000). Specifically, this is done by identifying structures in the causal loop diagram and associate them with perceived problematic issues. Focusing on a specific issue (or set of) involves excluding variables and casual relationships, re-evaluating their scope, and including additional variables and causal relationships. Re-evaluation of the scope becomes important because some variables and casual relationships can be relevant for multiple problem formulations, but with different impacts. The choice to focus on a specific issue (or a set of) also guides the subsequent model development by acting as a reference for queries regarding variables and casual relationships scope and relevance.

4 | CONCEPTUAL MODELLING AND PROBLEM FORMULATION IN RURAL ELECTRIFICATION

This section presents an application of the framework developed in Section 3 to rural electrification. It is divided into three subsections, each representing the steps outlined in the framework. The first step (Section 4.1) describes the development of an initial understanding of problems in rural electrification by extracting information about variables and causal relationships from literature and using existing knowledge. The second step (Section 4.2) describes the formulation of an initial causal loop diagram. The third step (Section 4.3) describes the process of developing a problem formulation from the initial causal loop diagram.

Research in rural electrification is multifaceted. Even though most research has been focused on technical and economic aspects, there is also a considerable (and growing) number of publications regarding political, social, and environmental consequences of rural

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[2]Containment refers to the mathematical relationship between two sets. A is contained in B if A is a subset of B or, equivalently, B is a superset of A.

electrification (Mandelli, Barbieri, Mereu, & Colombo, 2016). In addition, a considerable amount of research is done as case studies, presenting detailed information on local contexts. Even though rural electrification studies rarely collect (or report) information regarding either causal relationships or consider impacts as part of feedback loops, they often report causes and effects. However, neither the causes nor the effects are necessarily explicitly stated, and even if they are, their uncertainty might be high. As described in the framework, uncertainties are classified and then re-evaluated through increased knowledge. As knowledge is increased, causal relationships are better understood, which includes the relevant intermediate causal paths and their deviation from other sources of information.

Causal relationships are classified using the following procedure. Their uncertainty are classified by the type of line. Filled lines refer to a low uncertainty; dashed lines, to a medium uncertainty; and dotted lines, to a high uncertainty. In addition, casual relationships identified from literature are marked with black, those that are based on existing knowledge or assumptions are marked with red lines, and causal relationships identified from field work are marked with blue. Causal relationships are marked using +/− according to system dynamics practice.[3]

4.1 | Step 1: Formulating an initial understanding

The first step is to develop an initial understanding. This can be done by examining rural electrification literature in order to identify single or sets of causal relationships and their corresponding uncertainty. The identification was done by investigating statements and results reported in the literature. By evaluating the information provided from literature combined with previous knowledge on which the causal relationships are based, they were classified according to their estimated uncertainty as described in the framework.

One issue in rural electrification is that if tariff levels are high or inappropriate, large parts of the population (namely, the poor) are excluded. This is explained by Cook (2013):

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[3]A "+" sign on a causal relationship indicate that a change in the affecting entity and associated variable result in a change in the same direction in the affected entity and associated variable. A "−"sign on a causal relationship indicate that a change in the affecting entity and associated variable result in a change in the opposite direction in the affected entity and associated variable.

> *Tariffs are often skewed against the poor because they represent a higher risk category i.e. they have a greater tendency to default and have to be disconnected at a cost.*

The above statement can be described as the risk associated with connections impacts the tariff levels. With higher (perceived) connection risk, the tariff needs to be higher in order to economically justify the connection. The tendency to default a connection is likely due to the low income amongst the poor. In addition, it is likely that tariff levels affect electricity usage. This leads to the following causal diagram.
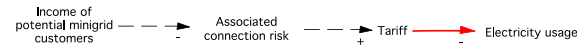
Furthermore, the low affordability of electricity prevent poor people to obtaining access, thereby increasing inequalities (Ahlborg, 2015; Cook, 2013). The affordability of electricity access is considered to consist of a connection fee (one-time cost) and tariffs (recurring costs). These processes are explained in the following causal diagram.
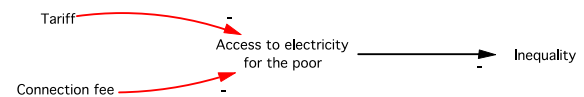
A topic of discussion in electrification and development literature is the relationship between access to electricity and economic (and social) development. It is commonly agreed that complementary services are needed. Specifically, introduction of complementary services, such as enterprise support packages, information, and awareness raising, will increase local economic opportunities (Bastakoti, 2003, 2006). In addition, it is possible that improved local economic opportunities will cause an increase in disposable income, which have been linked with increase in electricity usage (Bastakoti, 2006). These processes are represented by the following causal diagram.

Another process often mentioned when considering the link between electricity access and development is productive use. Productive use of electricity causes increased productivity (and thus revenues) as well as increased Income Generation Activity (IGA) opportunities. One such process is the ability to repair various tools, causing an improved agricultural potential (Kirubi, Jacobson, Kammen, & Mills, 2009). This is partly explained in the following statement from Kirubi et al.:

> *... local availability of electrical welding services for repairing tractors and other farm tools was*

the main mechanism through which electricity contributed to better exploitation of the agricultural potential in Mpeketoni.

Assuming that increased productivity and more IGA opportunities result in higher average income, the following causal diagram is developed.

Access to external markets is one of the main factors affecting income for business using electricity in rural areas (Kooijman-van Dijk, 2012). Access to external markets is amongst other linked with vicinity to roads (people can sell more goods due to an increased number of customers; Lenz, Munyehirwe, Peters, & Sievert, 2017). Furthermore, the vicinity to roads reduce connection costs (most distribution lines follow road networks, thus reducing infrastructure costs). The following causal diagram is obtained.
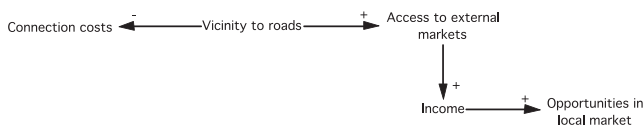
In addition, there have been studies showing an increase in employment (especially amongst women) in areas that have been electrified (Dinkelman, 2011). However, Dinkelman used national large-scale datasets and statistical methods, and could therefore not attribute the change to a specific process. As found by some, electrification increase the number and scope of IGAs (Cook, 2013), whereas this is challenged by others (Ahlborg, 2015). In addition, access to financial systems (such as microcredits) have been shown to impact the developments of new IGAs (Mulder & Tembe, 2008). These causal relationships are represented below.
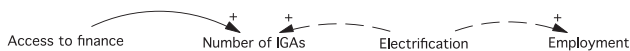
One challenge for mini-grids is to use installed generation capacity efficiently (e.g., high utilization factor). This means that generation capacity and demand should, to the highest degree, possibly match. The highest reported electricity demand in rural areas often occurs in the evening due to household demand. Raising electricity usage during the day (e.g., from IGAs) improve the utilization factor (Kirubi et al., 2009). Because improving the utilization factor corresponds to higher income without significant increase in expenditures, it improves operator economy, thus resulting in the following causal diagram.


Electricity quality and reliability is an issue in most developing countries and is important for IGAs relying on electricity (Mapako & Prasad, 2007). Reduced reliability, quality, and availability reduce productivity through loss of load or by compensating by the acquisition of backup generators (Dollar, Hallward-Driemeier, & Mengistae, 2005). Consequently, improving electricity quality (measured as less power outages and longer duration of supply) has substantial positive effects on non-agricultural income (Chakravorty, Pelli, & Ural Marchand, 2014). Furthermore, as reported by Cook (2013), amongst others, increase in income leads to increase in electricity demand. Thus, the following causal diagram is obtained.

One problem in rural electrification that is often mentioned by scholars is dispersed populations (Ahlborg & Hammar, 2014). Dispersed populations results in large connection costs (more infrastructure – electricity lines - needed for the average single connection) and larger operating costs (larger area to be covered and more infrastructure to maintain; Barnes & Foley, 2004). This results in the following causal diagram.

If a mini-grid is appropriately sized, unnecessary investment and operation costs can be avoided (Amutha & Rajini, 2016; Mandelli, Brivio, Colombo, & Merlo, 2016; Nfah & Ngundam, 2009). Assuming investment and operational costs affects tariff levels, lower expenses results in lower tariffs. Thus, the following causal diagram can be constructed.
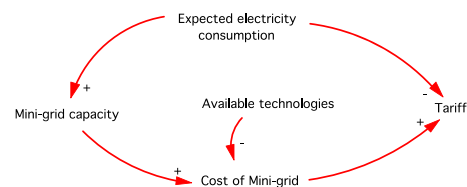
4.2 | Step 2: Formulating an initial causal loop diagram

The casual diagrams depicted above reflect explanations of causal relationships that sometimes involves the same

(or similar) processes or factors, such as, income and disposable income and IGA opportunities and number of IGAs. As described in the framework, entities and associated variables and causal relationships are merged in order to improve their relevance and usefulness and reducing the scope. When merging variables, it is important to keep a balance between what is known regarding entities (variables), their relationships, and available data. The study from Dinkelman (2011) on electrification's effect on employment found that electrification increased employment but actually decreased wages for women. This implies that the overall economic benefits might not be strictly positive, suggesting that there are additional causal relationships or feedbacks that were not considered in the study.

Furthermore, it is unlikely that merging the piece-wise causal diagrams in Step 1 will result in a causal loop diagram without any additional intervention from the modeller in terms of adding/modifying entities and/or relationships. Nevertheless, the merging of the piece-wise causal diagrams can raise questions that are fruitful in the modelling process. Specifically, this can be achieved by aiding in identifying "missing" variables and/or relationships, which are logically consistent with the model description but might not have been identified in the literature. One such example is the number of connections. The number of connections impacts electricity usage (the more connections, the higher electricity usage) and, in addition, the likelihood of obtaining a connection is

(amongst other things) likely related to income levels, connection costs, and operator resources.

Figure 2 shows the casual loop diagram based on the initial understanding as presented in the previous section. Because most of the causal relationships are not described as feedback processes, the casual loop diagram in Figure 2 has little focus on endogeneity. In addition, there are large uncertainties associated with causal relationships and their corresponding variables. Furthermore, the purpose of the conceptual model is still vague. Therefore, the diagram does not sufficiently well describe a problem formulation that can be further developed into a simulating stock-and-flow model.

4.3 | Step 3: Establishing a problem formulation

The purpose of the third step is to use the causal loop diagram in Figure 2 in order to develop an endogenous problem formulation. As described in the framework, focusing on an issue (or set of) and its associated problematic structures aids in developing the model purpose and reducing the problem scope. From Figure 2, it is noted that variables and causal relationships can be divided into three areas: technical (i.e., mini-grid capacity and available technologies), operation (i.e., tariff, operator economy, and cost of mini-grid), and socio-economic (i.e., income, productive use of electricity, and vicinity to roads). Due to the
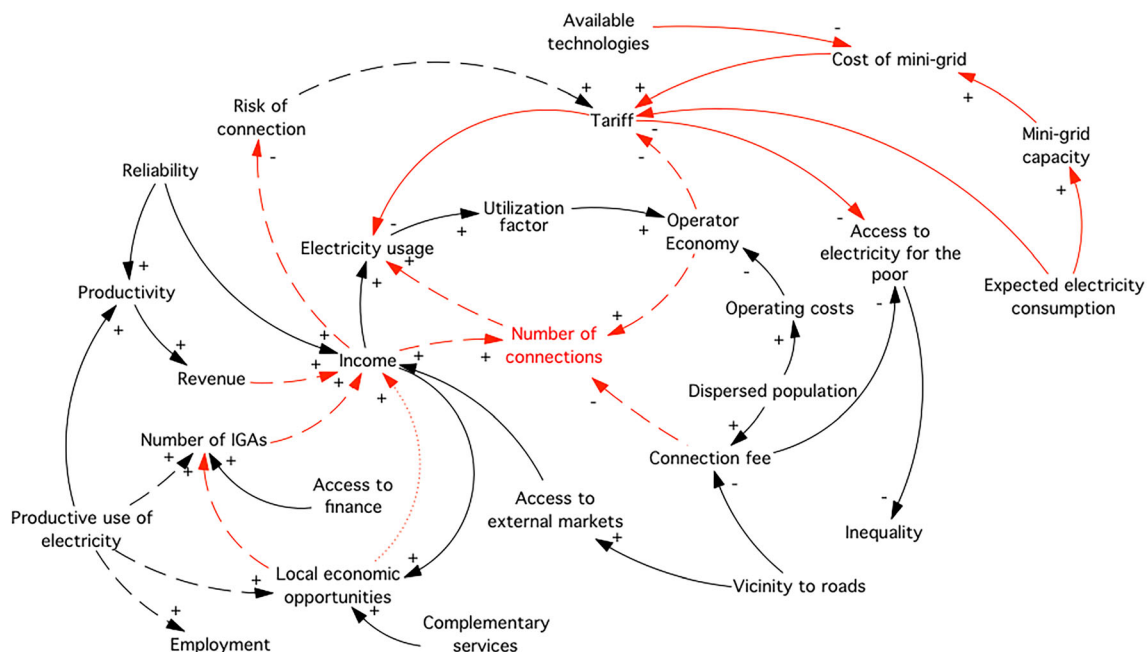
FIGURE 2 Initial casual loop diagram based on identified causal relationships from literature and assumptions. Additional (assumed) causal relationships are added in order to create the causal loop diagram and are marked as red and with dashed lines [Colour figure can be viewed at wileyonlinelibrary.com]

relationships shown in Figure 2, it is likely that a certain level of success is needed in each of these areas for a mini-grid to be long-term successful. Previous experiences from mini-grids has indicated long-term viability issues, associated with the mentioned areas (Ahlborg, 2015; Greacen, 2004; Taele, Mokhutšoane, & Hapazari, 2012), suggesting that operational entities and relationships constitutes an important problem. Thus, the following steps focus on the issues associated with the operation of mini-grids in relation to their long-term viability.

In order to re-evaluate the causal loop diagram in Figure 2 (as described in the framework), additional information is needed. In rural electrification, two sources of information are commonly used: literature and field work. Using literature as a source for information is resource-efficient. Nevertheless, literature is also limited in terms of scope and might not include the relevant information needed to operationalize the model. In addition, only using literature will limit the scope of data to only previously identified entities and relationships. Field work can, on the other hand, be tailored to collect data on issues identified by the initial causal loop diagram (Step 2), and might reveal new, previously unknown information.

By collecting data from the field, additional causal relationships and variables are identified, and uncertainty in already identified causal relationships can be reduced.

The diagram in Figure 2 is used to guide the subsequent data collection in order to reduce the number of "lose ends". A "lose end" is a variable that either; do not affect other variables; or is not affected by any other variable. By reducing the number of "lose ends", the number of exogenous entities and associated variables are reduced. It was noted in Figure 2 that reliability influenced a number of variables, but the literature lacked descriptions of variables and processes affecting reliability. During field work, three processes causing reliability issues were identified: overloading, low-quality components, and lack of repair and maintenance.

As described in the framework, the third step includes the re-evaluation of the scope of variables. In Figure 2, the variable "mini-grid capacity" was used. Initially, it described the installed generation capacity of the system (accumulated rated capacity of all generating devices). As such, it influenced reliability through overloading. However, reliability was also found to be affected by the overall functioning of the distribution system and its components. Mini-grid capacity was therefore revised to describe the functional capacity of the entire mini-grid. Functional capacity describes the actual available capacity and includes available generation and distribution capacity, which depend on correct maintenance and repairs.

By adding the causal relationships identified from the field, and by re-evaluating some of the variables in
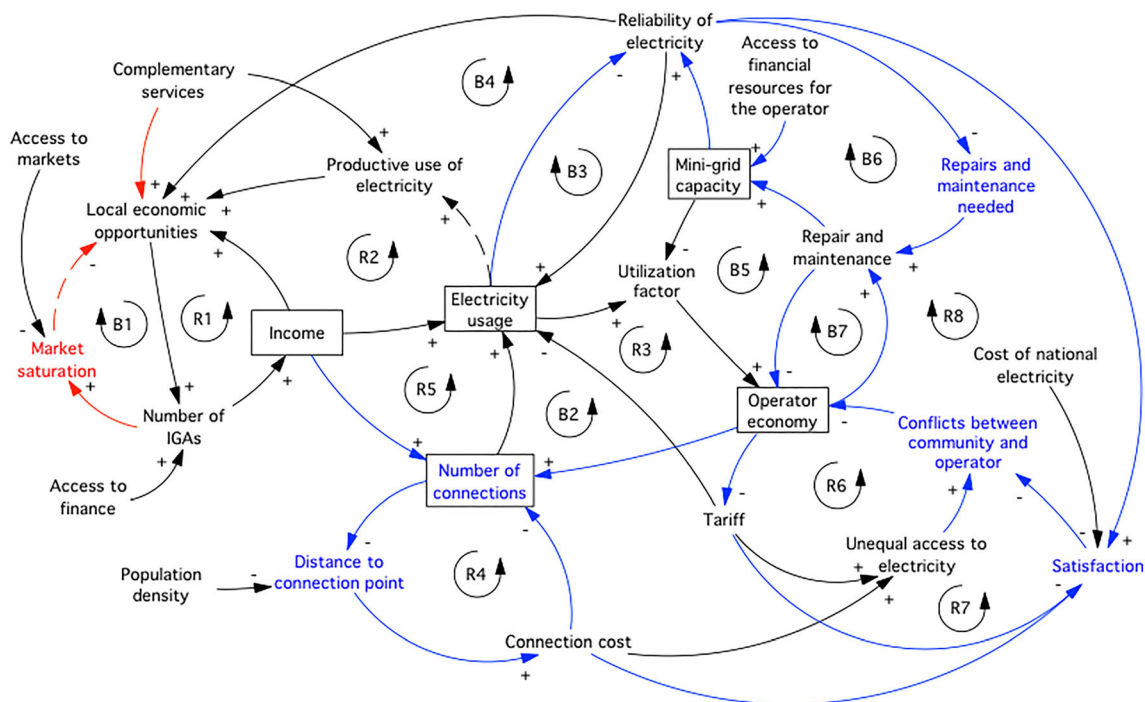
FIGURE 3 Causal loop diagram representing the problem of viability of a mini-grid in rural electrification. Black variables and causal relationships were identified in literature. Red variables and causal relationships are assumptions. Blue variables and causal relationships were identified from field work. Variables identified as relevant stocks are shown as boxes. The diagram shows eight reinforcing feedback loops (R1-R8) and seven balancing feedback loops (B1-B7) [Colour figure can be viewed at wileyonlinelibrary.com]

Figure 2, a new causal loop diagram was obtained as shown in Figure 3. Causal relationships and variables identified from field work (or those that had their uncertainty reduced due to verification through field data) are shown in blue in Figure 3. With the help of the reduced problem scope, relevant stock variables were identified (marked with boxes in Figure 3).

The causal loop diagram shown in Figure 3 contains eight reinforcing feedback loops (R1-R9) and seven balancing feedback loops (B1-B5). A few exogenous variables are also included as they are considered to be essential parts of the rural electrification process representing entities and relationships that are considered to be important intervention points in order to achieve successful (and likely viable) mini-grids (e.g., population density, cost of electricity in the national grid, and access to finances). The causal loop diagram in Figure 3 describes the problem of viability of a mini-grid in a rural electrification context. Furthermore, the causal loop diagram has a focus on endogeneity. Overall, the included causal relationships and variables have lower level of uncertainty due to the increased knowledge about the entities of their associated variables and causal relationships. The final casual loop diagram in Figure 3 represents a more precise purpose. It can therefore serve as a problem formulation and can be used in the subsequent system dynamics modelling process, either through a continued qualitative analysis or through development of a stock and flow model.

5 | CONCLUDING REMARKS

Previous system dynamics literature on the problem formulation process is scarce (Mashayekhi & Ghili, 2012), although it is considered to be one of the most important aspects of problem solving and is crucial when dealing with messy problems (Lyles & Mitroff, 1980; Vennix, 1999). In order to handle the difficulties of problem formulation, we have present a framework combining benefits from system dynamics and conceptual modelling. Below, we discuss the implications of our work from two different perspectives: First, the theoretical implications that our presented conceptual modelling process has on the problem formulation process in system dynamics and second, the implications in rural electrification.

5.1 | Theoretical implications

System dynamics was developed as a problem-solving method, and has in this regard, been very successful. Due to system dynamics focus on feedback, stocks and flows, and endogeneity, not all problems are suitable to be tackled by system dynamics. This suggest that the problem formulation process is important. Although there are considerable conceptual tools available within the system dynamics method, their application to problem formulation has been limited. Previous work has focused on using conceptual tools, such as causal loop diagrams, in the conceptualization or model development phase, which takes place after problem formulation. A successful example is group model building (Vennix, 1996), where causal loop diagrams can be used as a conceptualization tool for eliciting mental models from actors, but relies on an initial specified purpose or problematic behaviour.

This work contributes to the existing literature on applications of causal loop diagrams as a conceptual tool in system dynamics. We have shown that causal loop diagrams can be used as an aid during the problem formulation process. Compared with current applications, the main difference of causal loop diagrams—qualitative analysis (Coyle, 2000) and problem conceptualization (Vennix, 1996; Wolstenholme, 1992)—is that we have used causal loop diagrams earlier in the modelling process, and thus aided the problem formulation. This was achieved using the conceptual properties of meaning and ambiguity of causal loop diagrams to tackle uncertainties and lack of knowledge.

We described the process of using causal loop diagrams as a conceptual modelling tool through three stages. These stages each describes important steps in the problem formulation process, and the role of causal (loop) diagrams in each stage. Each stage demonstrates a procedure of how knowledge is increased and uncertainties are reduced. An important part of the conceptual framework is the characterization of uncertainties. Even though it is preferable to eliminate all uncertainties, it is not possible. As presented in the final causal loop diagram in Figure 3, a number of causal relationships were still, to some degree, considered uncertain. Regardless if the causal loop diagram is used for constructing a stock and flow model or for a qualitative analysis, this uncertainty needs to be taken into consideration in the subsequent modelling process.

Our work is limited to the early phase of problem formulation, which is characterized by a lack of knowledge and high uncertainties. Significant issues also lie in the later phase of problem formulation. Previous work in system dynamics and messy problems that focused on the later phase of problem formulation also included belief and value systems amongst actors and their corresponding impact on problem identification (Eden, 1994; Vennix, 1999). The impact of belief and values systems are important in situations where political views strongly

influence complexity reduction. Rural electrification can be described as a political process (Ahlborg, 2015), which suggests that belief and value systems are important and should be considered in the later phase of the problem formulation process. In addition, the conceptual framework was developed based on issues identified in the problem formulation phase in rural electrification. Even though similar issues might arise during the problem formulation phase in other areas, other methods could be more suitable.

5.2 | Implications in rural electrification

Problem formulation in rural electrification is challenging, and there is a lack of literature that has explicitly investigated it. The large number of variables, interactions, and messiness in rural electrification suggests that problem formulation is important but not trivial. Consequently, the previous lack of identifying and tackling the complexity (Ramalingam et al., 2008) and messiness in rural electrification has probably led to ambiguous problem definitions. The large number of interactions between elements and contradicting outcomes from previous studies suggests that it is important to consider systems effects. By applying our conceptual framework in rural electrification, we showed how it could be used to tackle the complexity and deal with uncertainties in variables and causal relationships, and thus aid in the problem formulation process.

The work contributes to current work in rural electrification in two areas. First, by using our framework to aid in problem formulation in rural electrification, we have presented a method for how to reduce uncertainty and increase system understanding in rural electrification related to the problem formulation phase. This has methodological implications in rural electrification. Specifically, it highlights the importance of systems methods when tackling problems in rural electrification. Applying reductionist methods in such instances might result in misunderstandings and possible erroneous explanations. Second, we show that many interactions relevant to mini-grids and rural electrification are dependent on feedback. This suggests that the behaviour related to the operation of mini-grids can be explained by endogenous dynamics and might not be dependent on exogenous factors. System dynamics is, therefore, an appropriate method to analyse the operational behaviour of mini-grids. The analysis can either be done through a continued qualitative analysis or through the formulation of a simulation (stock and flow) model.

An important part of the conceptual framework is the characterization of uncertainties. Even though it is preferable to eliminate all uncertainties, it is likely not possible. As presented in the final causal loop diagram in Figure 3, a number of causal relationships were still to some degree considered uncertain. Regardless if the causal loop diagram is used for a qualitative analysis or for constructing a stock and flow model, this uncertainty need to be taken into consideration in the subsequent modelling process. Because the uncertainties in the causal loop diagram indicates structural uncertainties, special attention should be taken during the structural validation process. A number of tools for analysing structural uncertainties in system dynamics are available. For stock and flow models, this includes linking behaviour and parameter space through simulations (Pruyt & Islam, 2015).

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