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Sustainable Energy Access for All:

Initial tools to compare technology options and costs

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Abstract

This thesis presents analytical advances to support quantitative insights into national and local policies for achieving energy access goals. The key objective is the creation of an analytical tool to compare technology options for achieving energy access goals and to estimate the cost of reaching those goals. To achieve that objective, the thesis is divided into three interconnected and complementary foci.

A pillar for such an analytical tool is an effective energy access metric. As the old adage goes: *you cannot manage what you cannot measure*. Therefore, the first focus of this thesis is on aspects of measuring energy access. In this thesis, energy access is not considered as a binary metric (access or no access) but as a service-oriented metric including information on how energy is used. Measuring the status of both current and future energy access-and-use goals (as well as tracking the progress in between) is crucial for supporting planning and choosing technology approaches. Different metrics are investigated and priority is given to two families of metrics: those useful for tracking the progress of energy access-and-use with available data, and those adequate for supporting future energy planning. In this context, special emphasis is given to one metric for each of these two groups: first to the Multidimensional Energy Poverty Index (MEPI) and second to the World Bank's Multi-Tier framework. The MEPI is assessed for as wide a set of countries as possible. The index appears effective to evaluate the status and recent trends in energy access-and-use at the national and regional scale with readily available data. For instance, MEPI results show how the intensity of energy poverty consistently decreases over time in all countries considered. Foci two and three of this thesis rely on the Multi-Tier framework. The Multi-Tier framework appears to be effective (and increasingly adopted) for setting energy access targets and evaluating the implications of those targets on technology choices and costs.

The second focus of this thesis concentrates on a limited set of case studies to gain insights and develop tools for policy support and national energy planning (focus 3). In fact, information from local energy access studies might be scaled up to advise national and regional-scale energy access planning. In this part, three case studies are evaluated. The first is a multi-criteria analysis (MCA) comparing electrification options in the Brazilian Amazon that explores selected techno-economic, environmental, social and institutional criteria. The multi-criteria analysis shows how renewable and hybrid systems present a number of advantages for application in isolated areas of the region compared to the current dominate practice of using diesel generators. Furthermore, the study outputs reveal key drivers to consider when choosing among electrification options. This provides a basis for contextualizing the electrification tool developed in focus three of the thesis. Specifically, techno-economic criteria provide the backbone of the tool while the remaining parameters offer guidelines for its case-by-case implementation. The second study focuses on the cost-comparison of technology approaches for electrification and cooking. A local level energy

system optimization model for a rural village in Timor Leste shows that, in the period 2010-2030, achieving the highest tier of electricity access could be as much as 75 times more costly than achieving the lowest tier. In addition, when moving across tiers, least cost solutions shift from stand-alone to mini-grid and finally grid connected options as electricity access increases. On the other hand, regarding cooking, moving from open fires to some of the more modern solutions has the potential to reduce overall costs over the same period. In the case study, the determinants of the costs of electrification projects are identified. These include (i) target level and quality of energy access, (ii) population density, (iii) local grid connection characteristics and (iv) local energy resource availability, fuel type and technology cost. The third case study analyzes the role of productive uses of energy for both local development and energy access. It adds a piece in the energy access puzzle looking both at the role and costs associated with energy in productive activities, and at the potential role of productive activities for powering rural populations up to different tiers of energy access. The analysis develops an analytical framework to assess and support productive uses of energy in agriculture. The resulting framework is then applied to a specific case of sisal production in rural Tanzania. Results from the case study show how combining the planning of energy access with productive uses could result in win-win-win solutions for the local utilities, companies and residents. This case study provides essential insights into how new policy tools may develop, moving beyond simple household use.

Finally, the third focus area expands and applies insights gained from the previous case study sections to develop generalized, simplified and scalable models. Key outputs from this thesis thus include both a tool and its corresponding guidelines. The first thesis output considers a deliberately simple model for comparing technology options that support electricity access-and-use goals. The second thesis output provides a series of suggestions for using it to inform electrification planning. When given an electricity access target, the tool permits a cost-comparison of technology approaches under a combination of local characteristics such as population density, resource availability, fossil fuel prices and generation technology costs amongst other things. Furthermore, the cases studies developed in focus two of the thesis provides guidelines on how to structure similar tools for cooking energy access and energy for other productive uses. The easily adaptable model is developed in such a way that it might also be used in geo-spatial toolkits, the utility of which is demonstrated in country specific, geographic information system (GIS) based, electrification analyses. These include applications to Nigeria, Ethiopia and India, presented in this dissertation, as well as to the case studies of all 48 countries of Sub-Saharan Africa, developed in subsequent work to this dissertation. The applications of the tool show how the strategy for expanding electricity access may vary significantly both between and within given regions of energy-poor countries.

Sammanfattning

Denna avhandling presenterar analytiska framsteg för att stödja nationell och lokal politik för att uppnå mål för energitillgång. Huvudsyftet med avhandlingen är att skapa ett analytiskt verktyg för att jämföra tekniska alternativ för att uppnå mål för energitillgång samt att uppskatta kostnaderna för att nå dessa mål. För att nå detta syfte är avhandlingen indelad i tre sammanhängande och kompletterande fokusområden.

En grundpelare för ett sådant analysverktyg är effektiv tillgång till energistatistik. Utifrån ordspråket *you cannot manage what you cannot measure* behandlar avhandlingens första fokusområde olika aspekter av att mäta tillgång till energi. I denna avhandling betraktas inte tillgång till energi som ett binärt mätvärde (tillgång eller ingen tillgång), utan som ett serviceinriktat mätvärde som inkluderar information om hur energin används. Mätning av status för både nuvarande och framtida mål rörande energitillgång och -användning (liksom för att spåra framsteg däremellan) är avgörande för att stödja planering och välja tekniska metoder. Olika mått utreds och två grupper av mått prioriteras: mått som är användbara för att spåra utvecklingen av energitillgång och -användning med tillgängliga data, och mått som är tillräckliga för att stödja framtida energiplanering. I detta sammanhang läggs särskild tonvikt på en måttenhet för var och en av dessa två grupper: det så kallade multidimensionella energifattigdomsindexet (MEPI) avseende den förra och Världsbankens så kallade Multi-Tier-ramverk avseende det senare. MEPI bedöms för en så bred uppsättning av länder som möjligt och indexet bedöms effektivt för att utvärdera status och de senaste trenderna inom energitillgång och -användning på nationell och regional nivå med tillgängliga data. Exempelvis visar MEPI hur intensiteten av energifattigdom minskar konsekvent över tiden i alla länder som analyseras. Avhandlingens andra och tredje fokusområden förlitar sig på Multi-Tier-ramverket. Detta beror på att Multi-Tier-ramverket förefaller effektivt (och alltmer använt) för att ställa upp mål för energitillgång och för att utvärdera konsekvenserna av dessa mål utifrån teknikval och kostnader.

Avhandlingens andra fokusområde utgår från ett begränsat antal fallstudier för att få insikt och utveckla modeller (och i nästa steg verktyg) för politiskt stöd och nationell energiplanering (fokusområde 3). Information från lokala studier om energitillgång kan skalas upp för att ge råd om planering för energitillgång på nationell och regional nivå. I denna del utvärderas tre fallstudier. Den första är en multikriterieanalys (MCA) som jämför alternativ för elektrifiering i Brasilianska Amazonas och som undersöker teknisk-ekonomiska, miljömässiga, sociala och institutionella kriterier. Denna kors-kriterieanalys visar att det skulle innebära ett antal fördelar att använda förnybara energikällor och hybridsystem i isolerade områden i regionen jämfört med den för närvarande mest utbredda lösningen dieselgeneratorer. Dessutom avslöjar studiens resultat viktiga faktorer att beakta vid val av elektrifieringsalternativ. Detta ger en grund för att kontextualisera elektrifieringsverktyget som utvecklas inom ramen för avhandlingens tredje fokusområde. Specifikt innebär detta att teknisk-ekonomiska kriterier utgör verktygets ryggrad medan övriga parametrar ger riktlinjer för dess genomförande från fall till fall. Den andra fallstudien fokuserar på kostnadsjämförelser av tekniska strategier för elektrifiering och matlagning. Den optimeringsmodell på lokal nivå som används avseende energisystem för en landsygdby i Östtimor visar att kostnaderna kan vara upp till 75 gånger högre för att tillgodose den högsta nivån av energitillgång jämfört med den lägsta under perioden 2010-2030. Dessutom kan den mest kostnadseffektiva lösningen variera beroende på vilken nivå

av energitillgång som analyseras, från fristående elgeneratorer till lokala nät till nätanslutning. För matlagning, å andra sidan, kan en övergång från öppen eld till några av de mer moderna lösningarna ha potential att minska de totala kostnaderna under samma period. I fallstudien har faktorer som påverkar kostnaderna för elektrifieringsprojekt identifierats. Dessa inkluderar (i) målnivå och kvaliteten på tillgång till energi, (ii) befolkningstäthet, (iii) Kriterier för lokal nätanslutning och (iv) lokala energiresurstillgångar, bränsle och teknologier. Den tredje fallstudien analyserar rollen som produktiv användning av energi har för både lokal utveckling och utvecklingen av energitillgång. Det lägger till en pusselbit i energitillgångspusslet genom att titta både på rollen och kostnaderna som kan kopplas till energi i produktiva verksamheter, och på den potentiella roll som produktiva verksamheter kan ha för att driva på energitillgången på landsbygden. Analysen utvecklar ett analytiskt ramverk för att bedöma och stödja produktiv användning av energi. Ramverket tillämpas sedan på specifika fall av sisalproduktion på landsbygden i Tanzania. Resultat från fallstudien visar hur man genom att kombinera planering av energitillgångsutveckling med produktiva mål kan uppnå så kallade ”win-win-win-lösningar” för lokala kraftbolag, företag och invånare. Även om denna fallstudie inte skalas upp i det tredje fokusområdet, ger den viktiga insikter om hur nya politiska verktyg kan utvecklas, och gå längre än enkel hushållsanalys.

Det tredje fokusområdet utvidgar och tillämpar slutligen de insikter som nåtts genom de fallstudierna för att utveckla generaliserbara, skalbara och förenklade modeller. Nyckelresultat från avhandlingen omfattar således både ett verktyg och dess motsvarande riktlinjer. Det förra avser en medvetet enkel modell för att jämföra tekniska alternativ som stöder mål för energitillgång och -användning. Det senare innehåller en rad förslag för hur detta verktyg kan användas för att informera elektrifieringsplanering. För ett givet mål för energitillgång ger verktyget en kostnadsjämförelse av tekniska metoder utifrån en kombination av lokala nyckelattribut såsom befolkningstäthet, resurstillgänglighet, fossilbränslepriser och kostnader för olika produktionsteknologier. Vidare så ger de fallstudier som utvecklats i avhandlingens andra fokusområde rekommendationer för framtida införande av matlagning och energi för produktionsändamål i verktyget. Den anpassningsbara modellen är utvecklad för att även kunna användas i kombination med geospaciala verktyg, vars användbarhet demonstreras i landspecifika GIS-baserade elektrifieringsanalyser. Dessa inkluderar tillämpningar i Nigeria, Etiopien och Indien, som presenteras i denna avhandling, liksom i de fallstudier rörande alla 48 länder i Afrika söder om Sahara, som utvecklats i det fortsatta arbetet med denna avhandling. Tillämpningar av verktyget visar hur strategin för att öka tillgången till elektricitet kan variera avsevärt både mellan och inom givna områden i energifattiga länder.

List of appended papers

- Paper I Nussbaumer, P.; Fuso Nerini F.; Onyeji, I.; Howells, M.; *Global Insights Based on the Multidimensional Energy Poverty Index (MEPI)*. Sustainability. 2013; 5:2060-2076.
- Paper II Fuso Nerini, F.; Howells, M.; Bazilian, M.; Gomez, M.F.; *Rural electrification options in the Brazilian Amazon A multi-criteria analysis*. Energy for Sustainable Development. 2014; 20:36–48.
- Paper III Fuso Nerini, F.; Dargaville, R.; Howells, M.; Bazilian, M.; *Estimating the cost of energy access: The case of the village of Suro Craic in Timor Leste*. Energy. 2015; 79 :385-397
- Paper IV Fuso Nerini, F.; Andreoni, A.; Bauner, D; Howells, M.; *Powering production; The case of the sisal fibre production in the Tanga region, Tanzania*. Energy Policy¹. 2016
- Paper V Fuso Nerini, F.; Broad, O.; Mentis, D.; Whelsh, M.; Bazilian, M.; Howells, M.; *A Cost Comparison Of Technology Approaches for Improving Access to Electricity Services*. Energy. 2016; 95: 255-265

¹ In the final review stages

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Abbreviations and Nomenclature

CDM	Clean Development Mechanism
Cf	Capacity factor
COP21	2015 Paris Climate Conference
DG	Diesel Generator
DHS	Demographic and Health Surveys
GHG	Green House Gas
GIS	Geographical Information System
IEA	International Energy Agency
kWh	kilowatt-hour
LCOE	Levelized Cost of Electricity
LEAP	Long range Energy Alternatives Planning System
LED	Light Emitting Diode
LPG	Liquefied Petroleum Gas
LPT	Luz Para Todos (Light for All)
MARKAL	MARKet allocation energy model
MCA	Multi Criteria Analysis
MEPI	Multi-Dimensional Energy Poverty Index
MG	Mini Grid
NAMA	Nationally Appropriate Mitigation Action
NPC	Net Present Cost
O&M	Operation and Maintenance
OSeMOSYS	Open-Source energy MOdelling SYStem
PV	Photovoltaic
REDD	Reducing Emissions from Deforestation and forest Degradation
SA	Stand Alone
SDG	Sustainable Development Goal
SE4All	Sustainable Energy for All
TEMBA	The Electricity Model Base for Africa
TIMES	The Integrated MARKAL-EFOM System
UN	United Nations
UNIDO	United Nations Industrial Development Organization
US	United States
USD	United States Dollar
WB	World Bank
WEO	World Energy Outlook

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1. Introduction

*Sustainable Development Goal n.7:
Ensure access to affordable, reliable, sustainable and modern energy for all*

UN's Sustainable Development Goals, New York, 2015

This chapter introduces the dissertation's background, structure, objectives and research questions. It also introduces the publications that contributed to this thesis and frames them in the context of the final dissertation.

1.1. Background

Access to modern energy is essential at all levels of development, ranging from catering for basic human needs to fueling modern society [1]. Energy has been described as “the golden thread that connects economic growth, social equity, and environmental sustainability” [2]. It is recognized that lack of access to modern forms of energy presents a key barrier to human development [3]. More generally, modern energy availability, both in the residential and productive sectors, is a prerequisite for societies to move away from a subsistence economy and out of poverty [4].

Nevertheless, over 1.1 billion people in the world still lack access to electricity, and 2.9 billion people have to cook with solid fuels in conditions that are often polluting and harmful to their health [5]. Additionally, the expansion in population with energy access in the world is struggling to keep up with overall population growth. In fact, even though projections by the International Energy Agency (IEA) expect 1.7 billion people to gain access to electricity by 2030, around 950 million people will still lack electricity access by then [6]. To support energy development, the United Nations (UN) launched the Sustainable Energy for All (SE4All) initiative (2012) [7]. The goals of the SE4All initiative are to achieve universal access to electricity and other safe household fuels, a doubled rate of improvement in energy efficiency, and a doubled share of renewable energy in the global energy mix by 2030. Additionally, Sustainable Development Goal number 7 (SDG7) is to ‘ensure access to affordable, reliable, sustainable and modern energy for all’ [8]. In line with those goals, governments in energy poor countries are setting ambitious energy targets for their energy access plans. However insufficient financial resources, lack of effective planning, and rapid population growth are just some of the many challenges to achieving these goals.

Focusing on the analytical aspect of the energy access-and-use challenge, this thesis identifies some of the barriers and knowledge gaps that stand in the way of the achievement of the SE4All and SDG7 goals. Selected barriers (and related research questions) are presented below and this work makes modest, yet essential, contributions to overcoming them.

1.2. Literature review, knowledge gaps and resulting research questions

This section reviews analytical barriers and knowledge gaps for modelling efforts to support energy access-and-use planning. It presents research questions, organized in three foci, to address the identified knowledge gaps. All the presented research questions work toward the thesis objective, presented in section 1.3.

A first barrier both governments and international organizations face when planning for energy access is the lack of a common framework for setting access goals and designing tracking processes [7]. As a result, many governments set energy access targets with a low level of detail, looking at energy access as a binary metric (access or no access) and setting a percentage of population to be provided with energy access. But this approach provides no indication on the level of energy use being targeted, nor what services might be provided [9]. Looking at electricity access, powering a Light Emitting Diode (LED) light bulb may, for example, have a lower socio economic impact than cooking or operating pumps and computers. Access is required for both, yet usage levels and technology choices differ widely. This thesis therefore looks at energy access in a broader sense as energy access-and-use. Energy access is detailed with the services that it can provide, and to do so several metrics are assessed.

A number of metrics for tracking and setting energy access goals are being developed to address this barrier. Those metrics can be divided depending on the level of information aggregation ([10] [7]). Regarding the level of aggregation, two schools of thought clash: that of the ‘aggregators’ versus that of the ‘non-aggregators’ [11]. Supporters of the former argue for the value of single numerals to capture a broad, often elusive concept, whilst advocates of the latter underline the risk of reductionism and note the flaws of aggregation methods. Uni-dimensional (sets/dashboards of) indicators ([12] [13] [14] [15]) use single and easily interpretable metrics. Since they are disaggregated, they provide a clear message for single parameter situations. Interpreting them for dynamics that involve a larger number of parameters – e.g. for energy access – may however be difficult. The second category: composite indexes ([16]), are single numerals calculated from a number of variables. They present the advantage of supporting both complex trend representation and performance benchmarking. However, by combining different variables, these indexes have the drawback of reducing the information down to a single measure, causing a certain loss of granularity in the final information. A hybrid approach, where both single indicators and their resulting composite indexes are reported along with their values, could be an advantage. Finally multi-tier approaches ([14] [17]) relate the multifaceted nature of energy access to a pre-defined scale that takes into account a given list of parameters.

For this thesis, those metrics are further divided into those suitable for gaining macro-level information on the status of energy access in a region or a country and those which might better support future energy planning by enabling the development of energy models that estimate the cost of different technology approaches for achieving access-and-use goals. Both families of metrics are needed in the energy access challenge. Their application to one or the other context depends on the goal of the corresponding analysis.

To investigate the barrier described above, this thesis looks at which (and how) different metrics can be used in energy access-and-use monitoring and planning. The corresponding research questions are as follows:

Focus 1 (Tracking and defining goals for energy access-and-use), research questions:

- a) *What metrics are appropriate for tracking progress and monitoring energy access-and-use?*
- b) *And what metrics are appropriate for supporting energy access-and-use planning?*

The thesis thus develops and/or uses a specific framework for each of these two research questions: the Multi-Dimensional Energy Poverty Index (MEPI) [18] for (a), and the World Bank's Multi-Tier framework [7] for (b).

The MEPI brings the energy metrics discussion forward in two ways. First, the calculation is based exclusively on field surveys (The Demographic and Health Surveys datasets [19]). It focuses on actual bottom-up data describing energy-related deprivations on final energy services (what people ultimately want and need). The deprivation perspective of the MEPI places its emphasis specifically on the poor [20]. Second, it uses a hybrid approach - reporting both the final index values and the indicators that compose the index. Spanning different dimensions the MEPI considers a mix of indicators available from local surveys, and focuses on "how" and "if" certain energy services are provided.

On the other hand, for supporting the energy access-and-use modelling effort in this thesis, the World Bank's Multi-Tier framework is used. That is for a number of reasons. First, the Multi-Tier framework is rich in detail, with a considerable disaggregation level. For instance, both the cooking and electricity access parts of the framework have detailed appliance-level data associated to each tier of energy access. As a result, this framework is able to support energy models that relate energy services to adequate energy-technology mixes that provide them. No other tracking framework for energy access-and-use with such level of detail for both energy service demand and supply was found in existing literature. Additionally, a number of ongoing efforts promote the use of the World Bank's Global Tracking Framework for monitoring country progress towards Sustainable Energy for All. The metric has been adopted by the Sustainable energy For All initiative [5] and is being used for an increasing number of country surveys and studies worldwide [28]. In fact, numerous regional and

country-scale surveys are available and more are ongoing to gather information regarding this metric. Results from these surveys are being collected in a platform [29] that provides a useful starting point for energy access analyses. This presents an advantage compared to other existing metrics, where relevant data paucity is an issue. Finally, while not enough data is currently available for using the Multi-Tier framework for tracking past energy access-and-use progress, as more data and households surveys are carried out and harmonized using the Multi-Tier framework, a shift might happen allowing it to be used for monitoring progress in energy access as well.

While tracking energy access-and-use is crucial for setting realistic energy goals with limited budgets, the World Bank also suggests that energy access programs need to be guided by a transparent, long-term, multiyear vision that is supported by applied technology choice studies [21]. However, a barrier for that to happen is the lack of locally-specific tools to support policy makers and promote the adoption of cost-effective, technology-appropriate energy systems for energy access-and-use. In this context, the advantages of quantified models for supporting energy decisions are multiple. As no two energy systems are created equal, modelling can help analysts to compare diverse technological options for energy access without having to incur the upfront cost of actually building them. As a result, models can effectively provide insights needed for investment decisions and energy planning. Furthermore, adequate modelling can support the selection of energy systems with the lowest overall cost that meet different populations' energy access-and-use needs reliably.

Several studies looked at the potential costs and appropriate technology options for increased electricity and cooking access-and-usage. For instance, Howells et al. 2005 [22] created a rural energy optimization model for a South African village using the MARKAL modelling framework. Other publications focus on specific supply side technologies for increasing electricity access. They estimate, for instance, the cost of energy access using solar PV [23], biomass-based [24] hybrid [25], hydro [26], and decentralized electricity generation technologies [27], amongst others. Rahman et al. 2013 [28] compared the LCOEs of several electrification technologies. A review of models for electricity supply and planning in rural or remote areas is available in Rojas-Zerpa & Yusta 2014 [29]. Further, other studies used modelling approaches to estimate country or global costs for access to electricity. A review of those is presented in Bazilian et al. 2014 [30]. Also, the International Energy Agency provided estimates for the technologies and costs for achieving increased access to electricity in Sub-Saharan Africa [31] and in India [32].

However, in the models mentioned above, some shortcomings were found that might limit their applicability for supporting energy access-and-use planning. First, none of the models above is related to the World Bank Multi-Tier framework, which is a key framework for the reasons described above. Other models focus either on a single technology or aggregate urban, peri-urban and rural areas in large regional or global models which lack the technology detail needed for representing the possible array of solutions that will be needed to achieve

energy access-and-use goals in a least cost manner. And finally, most of the models listed above are not open-source. This limits their adoptability for analysts in low- and middle-income countries, as well as easy reproducibility [33].

Another barrier that was found for supporting energy access-and-use planning is a lack of literature available relating energy models and productive uses in rural areas [34]. This is a crucial gap. Brew-Hammond 2010 [35] suggests that greater emphasis should be placed on productive uses of energy and specifically energy for income generation. The World Bank states that productive use of electricity should be considered in the bundle of services to be provided [21]. Thus, income-generating activities provide a means to effectively break the poverty spiral and therefore support for increased energy access. At the same time, modern energy access is crucial for most income-generating activities. Previous research looked either at practical guidelines for using energy in productive activities (such as [36]), at the implementation of renewable energy in productive uses [37], or included productive uses of energy in country- and regional- level models (as in the South African TIMES model [38]), thus with low level of technology detail on the productive uses side.

To start addressing the two barriers of lack of locally-specific tools for energy access-and-use and considering energy for productive uses, the following questions were selected for the second focus of the thesis:

Focus 2 (Case study analyses), research questions:

- c) *What criteria could be considered for comparing technologies for electricity access-and-use in energy planning?*
- d) *How could a least-cost, technology rich, bottom-up model assessing the cost of supplying different levels of electricity and cooking access be structured?*
- e) *And how might the link between energy and productive activities be described in a similar framework?*

These research questions are addressed with three local case studies. Each one is associated to a publication appended to this dissertation (Papers II, III and IV). The selected site specificities studied in this part of the thesis will then be used for looking at how a generalized model could be structured to be widely applicable to energy access-and-use planning.

Research question (c) is addressed looking at a case study in the Brazilian Amazon. This study develops a comparison of electrification technologies using a multi-criteria analysis (MCA) method. MCA methods aim to improve the quality of decisions involving multiple criteria by making choices more explicit, transparent and consistent. In the case study, techno-economic, environmental, social and institutional criteria are explored. In doing so, it helps to contextualize modelling efforts (that are in the techno-economic sphere) into the broader energy access challenge. Research question (d) is explored developing a rural energy optimization model for a village in East Timor. That study contextualizes the site-specificities

needed for electricity and cooking access-and-use techno-economic models. Finally, research question (e) is addressed by developing a case study in rural Tanzania that makes a first attempt at modelling the link between production activities and their specific energy needs.

These case studies, functionally calibrate models that compare technologies and costs for electricity access-and-use, cooking energy access-and-use, and access to energy for productive uses. The final focus of the thesis looks at how the dynamics seen in the case-studies described above can be generalized into a widely adaptable and simplified model.

To that end, another key barrier that this thesis discovered, is the absence of a simple and widely adaptable tool for evaluating technologies and costs for meeting 'Tiers of Access'. Yet, this is vital knowledge in terms of understanding the cost of meeting policies that will be tracked in terms of Tiers. Such a tool should be available for rapid 'first pass' assessments of electrification that might easily be taken up by (and indeed inform) extensive analysis, such as geo-spatial electrification mapping. Without these it is difficult to gain ready access to insights relating to what macro investments need to be made, in what technology and where.

Relevant efforts for generalized models for low and middle income countries found in literature are either complex [39] [40], or deeply embedded in the model coding [41] efforts. Szabó et al. 2013 [42] mapped the levelized costs of electricity of distributed solar and diesel generators and compared it to grid extension. However, the technology detail in this last study is limited and it is not applied to the World Bank Multi-Tier metrics. On the other hand, models available and used in high-income countries cannot properly address the energy access challenges. Such software can be expensive and thus not easily deployed [43]. The dynamics modelled and the emphasis of the analysis may have a different focus. In high income countries, energy access has given way to GHG mitigation, security and other issues. There is often limited data. And local skills and capacity to take on existing systems may be limited. This makes the utility gained by an elegant open model – without trivialization – clear. New tools have to be designed and tailored for the energy access challenges that low- and middle- income countries face [44]. Open-access and simplified models for the optimal allocation of economic resources have the potential to lower the barriers for adoption, and ease repeatability [33], in particular for analysts in developing countries.

Given this last barrier, Focus 3 of the thesis address the following research questions:

Focus 3 (Development of a simple analytical tool to support technology choice and budget allocation in national energy access-and-use planning), research questions:

- f) *What could the structure of a techno-economic model for comparing and allocating costs to electricity access options for a large number of site specific settlements throughout a country look like? What are its main determinants? How might it be translated into national strategies?*

g) How might similar techno-economic models for access to cooking and productive uses be structured? How could such tools be merged with the electricity access-and-use tool presented in this dissertation?

Research question (f) is addressed developing a deliberately simple and site-specific tool for comparing technology approaches and directing investments for electricity access in the context of the World Bank Multi-Tier framework. While it is site specific enough to capture key local dynamics, it is simple enough to be rapidly deployed to the thousands of settlements that needs to be evaluated in regional-scale electricity access planning, and for developing general, national level, information. The tool includes both a mathematical model and a series of application guidelines.

In the case study section access to electricity, productive uses of energy, and energy for cooking are discussed. The model for electricity access is developed further in this thesis. Additionally, guidelines for the development of similar models for productive uses of energy and cooking energy access are presented, thus addressing research question (g).

1.3. Thesis objective

Given the research questions listed above, the final objective of this thesis is to develop an open and simple tool to evaluate technology and costs trade-offs for achieving useful energy access-and-use goals. This tool should be based on insights from case studies that help identify what local, specific, information provides sufficient – yet not excessive – complexity for it to be applied generically. It should be designed around data limitations, and both ‘inform the design of’ and be ‘adoptable within’ efforts that rapidly assess all settlements within a country or continent².

In this thesis the tool for electricity access-and-use is developed. Subsequent collaborative work is reported, which demonstrates its utility at national and continental levels. Also, guidelines for developing similar tools for cooking and energy for productive uses access are provided.

There are many issues not addressed in this thesis. These include, for example, an analysis of behavior, institutions and technology diffusion (see a more complete discussion of the limitations of this thesis work in Section 4.1, Thesis limitations). While these are very important, this thesis delineates a narrow and specific set of additions, providing more (or sharpened) tools to the energy access analyst and for local practitioners. As demonstrated with country level assessments and subsequent usage of the tool (see Section 4.2, Impact of the thesis work), these additions are useful and impactful.

² Such an assessment should be able to inform questions, such as: what technology mix and costs are incurred by the provision of electricity at different levels of use for a given country, region or even the globe.

1.4. Thesis target audiences

Multiple audiences are targeted by this thesis, namely:

- Analysts and policy makers in local and national governments who have the task of designing policies, allocating funding and mobilizing technology deployment for energy access.
- International organizations and donors supporting countries' energy access strategies and allocating funding for energy access projects
- Energy service companies who seek to understand potential markets for technologies, systems and services
- And, the broader international energy research community focusing on addressing challenges associated with SDG7: ensure access to affordable, reliable, sustainable and modern energy for all

1.5. Thesis structure

The thesis is divided into a cover essay and five appended papers.

The cover essay is divided into four parts. The first chapter introduces the general framework for the thesis. This includes positioning the thesis within existing academic research while establishing its aims, objectives and research questions. The second chapter contains the methods section and discusses the research methodology. The third discusses results and implications of the research. Finally, the fourth discusses the limitations and possible future research and highlights the impacts of the thesis' outputs.

Additionally, the dissertation includes five appended research papers. Independent and yet interconnected, they include the bulk of the research work presented in this thesis. At the time of writing, four of the five papers are published in refereed international journals. The fifth is accepted subject to a pending successful revision. The five papers are listed below, and the author's contributions to each paper briefly outlined:

Paper I

Nussbaumer, P.; Fuso Nerini F.; Onyeji, I.; Howells, M.; *Global Insights Based on the Multidimensional Energy Poverty Index (MEPI)*. Sustainability. 2013; 5:2060-2076.

Author's contributions to the paper: *The author of this thesis contributed to the paper with: MEPI algorithm refinement to include new datasets and to address data paucity issues³. Analysis of the Demographic and Health surveys for the calculation of all the MEPI country results. Analysis of the results including analysis of the MEPI determinants and sensitivity of the results. Section on data availability. Graphics, tables and MEPI mapping, including*

³ Only 29 countries were evaluated with the MEPI in previous efforts [40], and all located in Africa. For paper I, the author of this thesis recalculated all the MEPI for all those 29 countries with the newest datasets, and for other 25 other countries spread across the world.

Figures 1 and 2 and Table 2. Appendix A, B and C were also made by the author of this dissertation. The other authors developed the introduction and literature review, the MEPI algorithm as previous to this paper improvements, and counsel, supervision and editorial revisions to the paper.

Paper II

Fuso Nerini, F.; Howells, M.; Bazilian, M.; Gomez, M.F.; *Rural electrification options in the Brazilian Amazon A multi-criteria analysis*. Energy for Sustainable Development. 2014; 20:36–48.

Author's contributions to the paper: All fieldwork, analyses and substantial write up. The other authors contributed counsel, supervision and editorial revisions to the paper.

Paper III

Fuso Nerini, F.; Dargaville, R.; Howells, M.; Bazilian, M.; *Estimating the cost of energy access: The case of the village of Suro Craic in Timor Leste*. Energy. 2015; 79 :385-397

Author's contributions to the paper: All analyses and substantial write up. The other authors contributed counsel, supervision and editorial revisions to the paper.

Paper IV

Fuso Nerini, F.; Andreoni, A.; Bauner, D; Howells, M.; *Powering production; The case of the sisal fibre production in the Tanga region, Tanzania*. Energy Policy (final review stages). 2016

Author's contributions to the paper: All fieldwork. Most of the introduction and literature review. The methodology was jointly developed with the other authors. All the case study part, the techno-economic model and the results sections were developed by the author. Other additions from the co-authors contributed counsel, supervision and editorial revisions to the paper.

Paper V

Fuso Nerini, F.; Broad, O.; Mentis, D.; Whelsh, M.; Bazilian, M.; Howells, M.; *A Cost Comparison Of Technology Approaches for Improving Access to Electricity Services*. Energy. 2016; 95: 255-265

Author's contributions to the paper: experiment design, cost model development, results analysis and paper write up. The other authors contributed to the methodology refinement, to reviewing the paper, and to the production of some of the graphical results.

Each of the appended papers underpins or adds to one or more of the research foci presented in this dissertation. In Table 1 the papers are related to the foci. Also, in Table 2 the papers' contributions to the final thesis objective are presented.

Table 1 Relation between appended paper and research focuses in the thesis

Research focus	Paper				
	I	II	III	IV	V
1. Tracking and defining goals for energy access-and-use					
2. Case study analysis					
3. Tool development					

Note: Dark grey and light grey shaded cells represents papers that provided significant and moderate contributions, respectively, to the research foci of the thesis.

Table 2 Papers' contributions to the final thesis objective (see section 1.3)

Paper	Contributions to the final thesis objective
I	Assessment of energy access-and-use metrics: This paper's results and literature review were used to select the energy access-and-use metrics for the tool presented in section 3 of the thesis.
II	Preliminary assessment of the criteria to be considered when comparing electrification options. Techno-economic, environmental, social and institutional criteria are explored in the analysis. The final tool development in focus 3 builds primarily on techno-economic criteria, and uses the other evaluated criteria to provide guidelines for the implementation of the tool in diverse contexts.
III	The rural electricity access-and-use optimization model built for the case study provides a basis for the simplified electrification model adopted in focus 3 of the thesis.
IV	Comparison of energy access-and-use options for supporting productive uses of energy. This paper provides a link between the model developed in focus 3 of the thesis, which is applied in the paper for evaluating residential electricity access options, and productive uses of energy. While not included in that model, it provides useful guidelines for the potential and future inclusion of productive uses of energy in the tool developed in focus 3.
V	This publication presents the parameters and the structure of the model developed in focus 3 of the thesis. Additionally, applications of the tool to the countrywide cases studies of Nigeria and Ethiopia are presented.

Additionally, the following publications and author's contributions to reports and books provided useful insights to the thesis. These, however, do not represent an integral part of this thesis although some are referenced in sections of the cover essay and appended papers:

- I. International Energy Agency, *World Energy Outlook 2015*.** The contributions to the India Chapter reported in the spotlight section at pp. 561-562, 2015
- II. International Energy Agency, *India Energy Outlook 2015*.** Spotlight section in pp. 153-154, 2015

- III. Mentis, D. ; Welsch, M. ; **Fuso Nerini, F.** ; Broad, O. ; Howells, M. ; Bazilian, M. ; Rogner, H. ; *A GIS based approach for electrification planning - A case study on Nigeria*, Energy for Sustainable Development. 2015, 29:142-150
- IV. **International Energy Agency (IEA) and the World Bank**, *Sustainable Energy for All 2015—Progress Toward Sustainable Energy*, World Bank, Washington, DC. Contributions to the energy access and nexus chapters (pp. 243-280), 2015
- V. **International Energy Agency**, *World Energy Outlook 2014*. The contributions to the Africa Chapter reported in the spotlight section at pp. 540-541, 2014
- VI. **International Energy Agency**, *Africa Energy Outlook 2014*. Spotlight section in pp. 126-127, 2014
- VII. **Fuso Nerini, F.**, Ray, C., Boulkaid, Y., *Comparing cooking access options. The case of the Nyeri County in Kenya*, working paper, 2016

2. Methods

‘A precursor to effective action at the country level is a set of well-thought out plans and strategies for attracting, supporting, and streamlining investment’

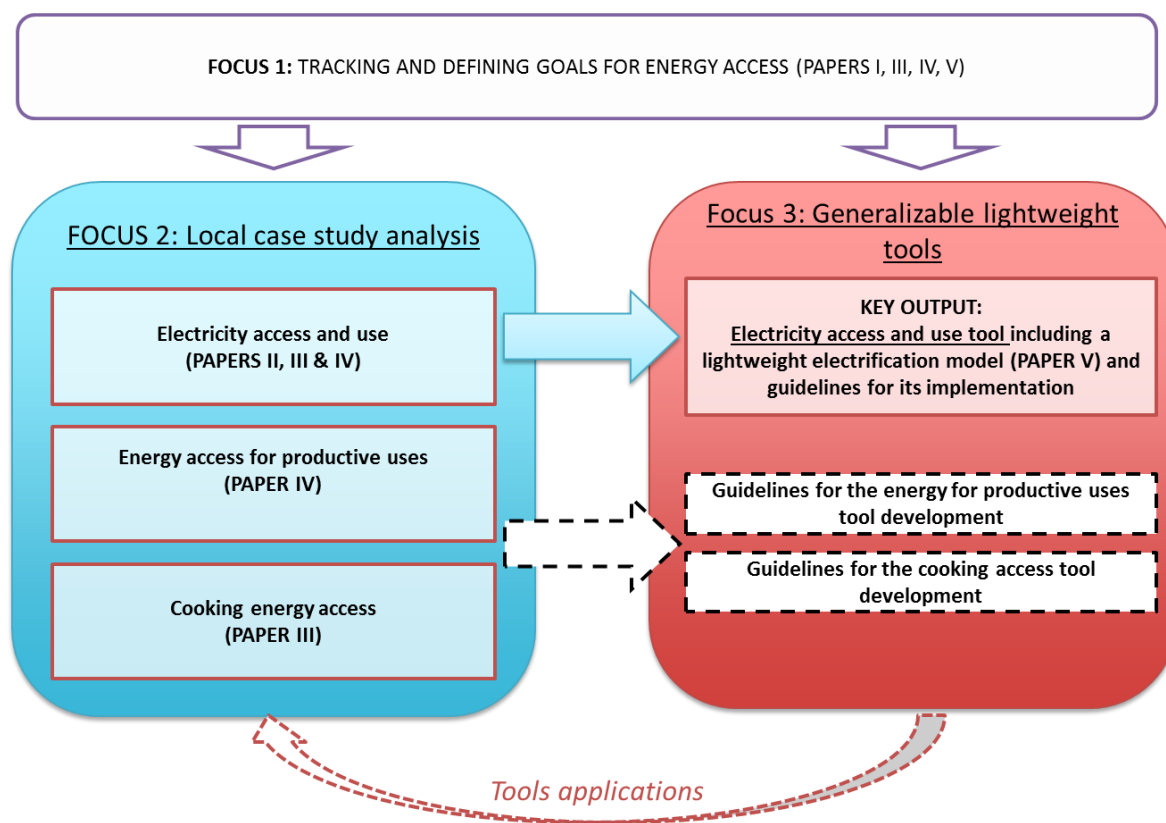
United Nations Sustainable Energy for All. A Global Action Agenda, 2012 New York

In this chapter the methodology of the dissertation is explained. This chapter is complementary to the methodologies presented in the five papers appended to the thesis.

The process adopted in the dissertation is represented graphically in Figure 1. Contributions from the five key research papers to the foci and their links are indicated. This section outlines the overall methodology – and those used in each foci.

The key research output from this thesis is presented in Focus 3. Focus 1 of the thesis informs Focus 2 and 3 by selecting energy access-and-use metrics to be used in the modelling efforts. Focus 2 develops three case studies that are then used as a basis for formulating the tool presented in Focus 3.

Figure 1 Methodology



2.1. Focus 1: Tracking and defining goals for energy access-and-use

The methodology for this section includes a literature review of existing metrics, and the development of specific methodologies for applying the corresponding metrics. As discussed in the previous section focus is given to two metrics: the Multi-Dimensional Energy Poverty Index (MEPI) and the Multi-Tier framework developed by the World Bank. The first was chosen as useful for tracking progress and monitoring energy access-and-use, and the second one for supporting energy access-and-use modelling efforts.

The MEPI is an index designed to capture and evaluate a set of energy-related deficits that affect a household. The index is composed of five dimensions, representing basic energy services, and six indicators (Table 3). The specific calculation methodology⁴ was – to some extent - designed based on the availability of survey data from the Demographic and Health Surveys database. These include survey data for over 90 countries [19]. The software used for calculating the MEPI was the statistical analysis software STATA [45]. The micro-level input data (households or individuals) allows a large number of disaggregated analysis by sub-groups (such as the sub-national level or by income category).

Operationally, the MEPI is divided in two parts. The headcount ratio H represents the proportion of people that are considered energy poor. The second part of the MEPI is the intensity of multidimensional energy poverty A . That is the average level of energy poverty for the surveyed households. Higher levels of A correspond to a greater energy poverty intensity. Considering q the number of energy poor people⁵ and n the total, $H = q / n$ represents the incidence of multidimensional energy poverty. The average of the weighted energy deprivation across the surveyed people represents the intensity of multidimensional energy poverty A . Therefore the MEPI captures information relative both to the incidence and to the intensity of energy poverty. It is defined by $MEPI = H * A$.

⁴ see paper I for full detail

⁵ The MEPI indicators are combined to form a weighted energy deprivation index. People whose index value exceeds a so-called ‘energy poverty line’ threshold are considered to be “energy poor”.

Table 3 Dimensions and respective indicators with cut-offs for the MEPI calculation, including relative weights in parentheses

Dimension	Indicator (weight)	Variables	Deprivation cut-off (energy poor if...)
Cooking	Modern Cooking fuel (0.2)	Type of cooking fuel	any fuel use besides electricity, LPG, kerosene, natural gas, or biogas
	Indoor pollution (0.2)	Food cooked on stove or open fire (no hood/chimney), indoor, if using any fuel beside electricity, LPG, natural gas or biogas	true
Lighting	Electricity access (0.2)	Has access to electricity	false
Services provided by means of household appliances	Household appliance ownership (0.13)	Has a fridge	false
Entertainment/education	Entertainment/education appliance ownership (0.13)	Has of radio OR television	false
Communication	Telecommunication means (0.13)	Has a phone land line OR a mobile phone	false

The MEPI is an example of a useful index for tracking progress on energy access-and-use. On the other hand, the Multi-Tier framework developed by the World Bank was adopted for supporting the modelling efforts presented in this thesis. The Multi-Tier framework was developed (and it is being continuously updated) for measuring access to energy for the household (such as electricity, cooking and heating), for productive uses, and for community uses [5]. In Figure 2 the framework reported for electricity services is reported. Each tier of access is categorized by the appliances that can be powered with a given level of electricity consumption. This thesis builds upon the Multi-Tier framework for electricity and for cooking access, associating the different tiers of electricity access to the potential costs and energy technologies required to meet them.

Figure 2 Multi-Tier matrix for measuring access to household electricity services, Source [5]

		Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Tiers	Tier criteria	—	Task lighting and Phone charging	General lighting and Television and Fan (if needed)	Tier 2 and Any medium power appliances	Tier 3 and Any high power appliances	Tier 2 and Any very high power appliances
	Indicative list of appliances		Very low power appliances	Low power appliances	Medium power appliances	High power appliances	Very high power appliances
Appliances	Lighting	—	Task lighting	Multi-point general lighting			
	Entertainment and communication	—	Phone charging, radio	Television, computer	Printer		
	Space cooling and heating	—		Fan	Air cooler		Air conditioner, ^a space heater ^a
	Refrigeration	—			Refrigerator, ^a freezer ^a		
	Mechanical loads	—			Food processor, washing machine, water pump		
	Product heating	—				Iron, hair dryer	Water heater
	Cooking	—			Rice cooker	Toaster, microwave	Electric cooking

2.2. Focus 2: Local case study analysis

Different, yet complementary methods are used in each case study of focus 2. Each method is designed to address a specific research question.

2.2.1. Case study 1: Comparing rural electrification options in the Brazilian Amazon

The objectives of this case study were to determine which criteria could be used to compare electrification options in energy planning, to explore how current popular solutions (e.g. diesel generator powered mini-grids) perform under the chosen criteria, and to compare selected technological solutions for providing electricity to the remaining non-electrified communities. To achieve such objectives, a Multi-Criteria Analysis was performed.

In the Multi-Criteria Analysis various assessment criteria are selected. The criteria for comparing electrification options were chosen after both a literature review and structured interviews with local stakeholders. These elements are assigned weights and aggregated into corresponding macro criteria, which in turn receive relative weights. The weights were

determined through stakeholder interviews, in which they expressed their judgment regarding the importance of one criteria over another using a questionnaire⁶ thus revealing the relative significance of each criteria for choosing between different electrification technologies. Finally, the resulting alternatives are prioritized and ranked [46]. The MCA is useful when considering several competing criteria in the decision making process⁷. Additionally, it allows the comparison of electrification options based on criteria, macro-criteria and the final composite index – which expresses an overall evaluation of the regional options.

The electrification options include diesel generators (DG) (the benchmark solution), solar PV systems, biomass-based systems, micro-hydro electricity systems, and hybrid⁸ electricity systems. The 16 criteria as well as the decision algorithm used to assess the final index of the analysis are reported in Figure 3. The criteria were assessed and compared by mixing literature review, field observations, and semi-structured interviews with local stakeholders. In the analysis, criteria are weighted (with a weight W_i [%]) to form the respective macro-criterion. The weights W_i were chosen pursuing a participatory approach: with semi-structured interviews to several local stakeholders. An outcome of this case study is therefore a list of criteria that help to compare electrification options along with their relative importance in the decision making process⁹.

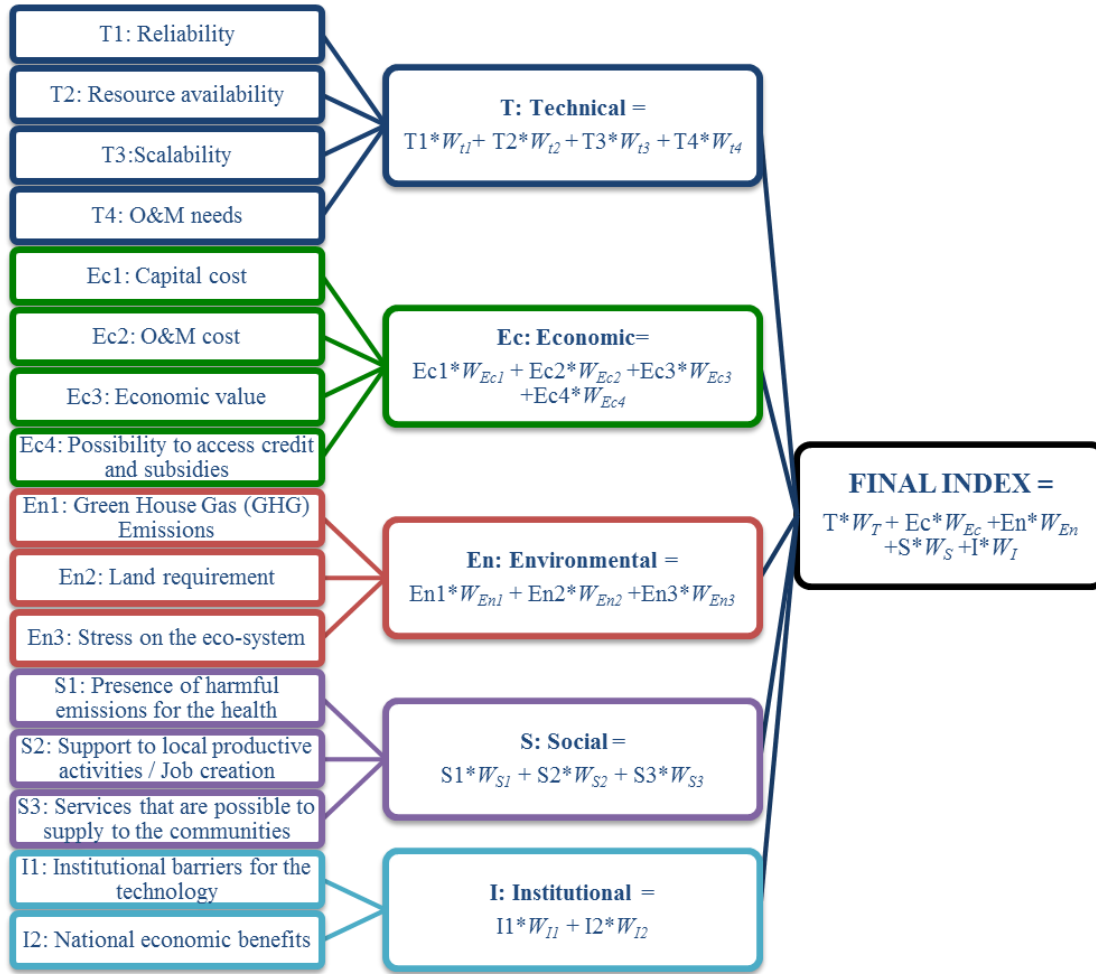
⁶ Reported in annex A of paper number 5

⁷ However, it is to be noticed that in the MCA there is not a detailed evaluation of the considered criteria: information might be lost in the evaluation due to the large amount of information needed to evaluate competing solutions with several criteria spacing in different dimensions.

⁸ ‘Hybrid’ energy systems are systems combining two or more technologies for supplying electricity (e.g. PV systems and diesel generators)

⁹ Additionally, the multi criteria analysis evaluation has the advantage of both assessing if current solutions and electrification programs are appropriate for the considered context. It gives suggestions for future energy access plans and projects. This in turn is useful for giving guidelines for the application of the tool developed in focus III of the thesis.

Figure 3 Algorithm for the Multi Criteria Analysis developed in paper II



2.2.2. Case study 2: Estimating the cost of energy access in rural Timor Leste ¹⁰

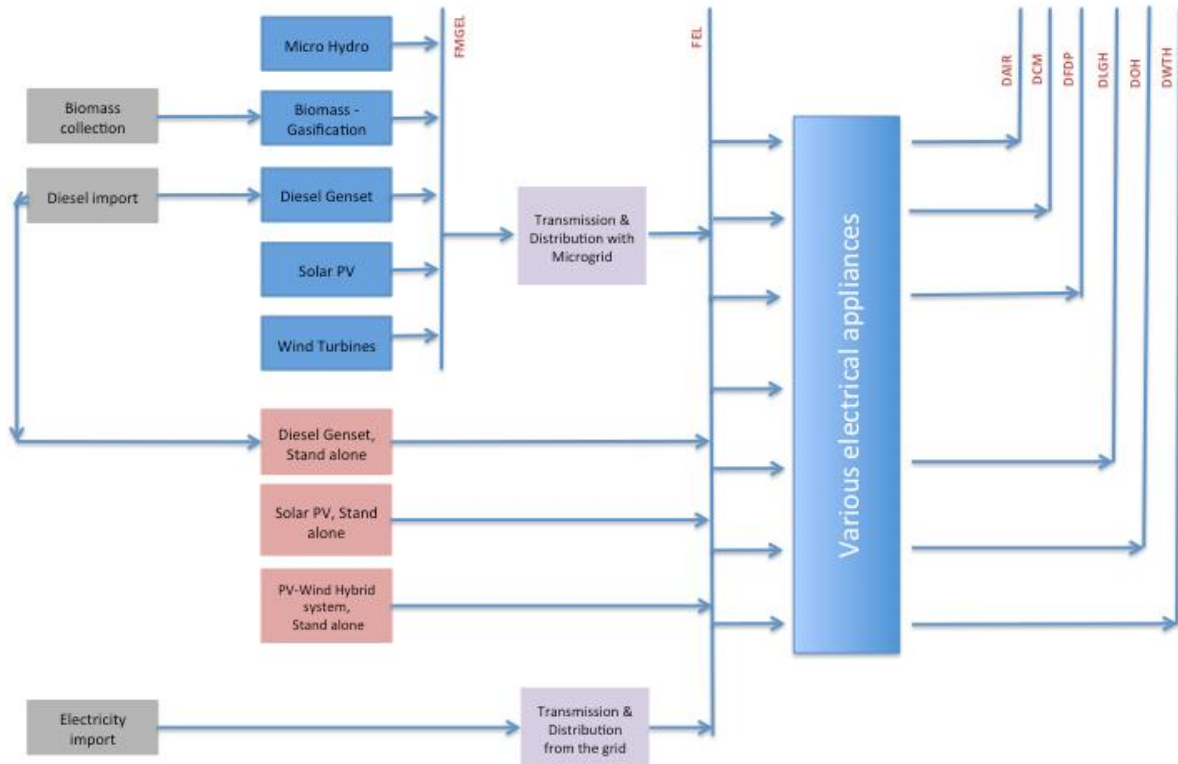
This case study presents the development of a bottom-up optimization village energy model. The model is built using The Open Source Energy Modelling System (OSeMOSYS) [47]. OSeMOSYS is a linear programming model of the same family as MARKAL [48], TIMES [49], and MESSAGE [50]. The objective of OSeMOSYS is to calculate the lowest net present cost (NPC) of an energy system to meet given demand(s) for energy carriers, energy services, or their proxies [47]. OSeMOSYS is useful for determining both internally consistent and optimal technology portfolios that meet a specific goal. Using the Multi-Tier framework, a village energy model was created to compare the cost-optimal electrification and cooking options required for reaching different tiers of energy access. This provides insights regarding both the technology and economic implications of achieving different levels of energy access. The electricity and cooking goals for the village were calculated starting from the WB Multi-Tier framework. The targets were added to current household demand that was estimated

¹⁰ see paper III for the detailed model description

using village surveys. The current cooking service demand was calculated based on average cooking times observed in the village.

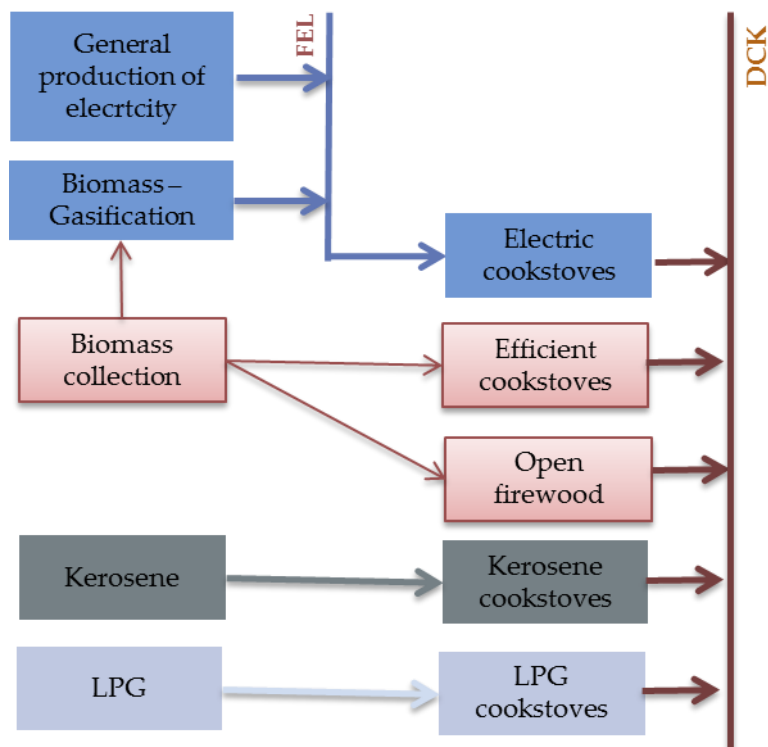
The model breaks the year down into 18 ‘time-slices’. This detail helps to represent the variability of the demands while also capturing the impact of local climate and typical load distributions that result from powering the Multi-Tier framework appliances. Two, interconnected, reference energy systems¹¹ were used to model the supply and demand of energy for both electrical and cooking uses in the village (Figure 4 & Figure 5). The electricity supply component of the model considers several electrification options divided among stand-alone, mini-grid and grid-connected options. Similarly, the cooking component compares traditional and modern cooking methods. Further detail was added with regard to resource availability and production limits for the electrification options. Finally, the model was run to evaluate several scenarios with different cost assumptions. Ultimately, this electricity access-and-use model was used as a starting point for developing the simplified electricity access-and-use tool presented in focus 3 of this thesis.

Figure 4 Electrical reference energy system for the electricity access-and-use optimization model



¹¹ A Reference energy system is a simplified network representation of the fuels, technologies and transformations used to supply energy to the different forms of end use activities.

Figure 5 The reference energy system – focus on the cooking options



2.2.3. Case study 3: Powering the agricultural production in the Tanga region, Tanzania¹²

This case study focuses on the role of modern energy access-and-use in productive activities and, vice versa, how productive activities can support energy access in the region. Concentrating on the rural agricultural sector, a micro-structural analysis was conducted¹³ in order to identify its key processes, tasks and technologies as well as their respective energy requirements. Reported in

Table 4, the results were used to create a case specific model analyzing the energy systems of sisal production activities in the Tanga region, Tanzania.

¹² A detailed description of both the model and the scenarios is reported in paper IV

¹³ This study analyses the structure of the rural agricultural sector and breaks it down into its key processes. These are then characterized using potential energy technologies and carriers that could support them. Further detail can be found in the appended paper number VI.

Table 4 Key agricultural processes in rural areas, and energy needs for traditional and modern methods uses as a structural basis for the model presented in paper IV

Processes	Tasks	Traditional methods & technologies	Energy sources	Modern methods & technologies	Energy sources
Primary production	Land preparation/ Tilling	Hand hoe, animal drawn tiller	Human and animal	Power tiller/two-wheel tractor	Fossil fuels, biofuels
	Seeding	Hand planting	Human	Bed planter, row planter/seed drill	Fossil fuels, biofuels
	Irrigation	Container/bucket for lifting + carrying water, wind pumps, rain fed	Human, animal, traditional renewable	Mechanical irrigation (with diesel pump, treadle pump, rope pump, ram pump, persian wheel, river turbine)	Fossil fuels, biofuels, electricity, mechanical energy, and direct usage of renewable energy (solar, wind and hydro)
	Fertilizing	Organic fertilizer	Human and animal	Organic and inorganic fertilizer applied with modern methods	Energy embedded in the fertilizer, fossil fuels, biofuels
	Harvesting	Scythe, animal drawn mower, manual practices	Human and animal	Harvester, attached to a power tiller/tractor	Fossil fuels, biofuels
Crop Processing	Drying	Hand-held fan, sun drying	Human, traditional renewable	Artificial drying, powered fan	Electricity, fossil fuels
	Milling, pressing	Hand ground, flail	Human	Electric motors, direct mechanical supply, powered mill, oil espellers	Electricity, fossil fuels, biofuels, mechanical energy
	Cutting, shredding	Knife	Human	Saw mills, power shredder	Electricity, fossil fuels, biofuels, mechanical energy
	Winnowing, decorticating	Winnowing basket	Human	Powered shaker, grinders	Electricity, fossil fuels, biofuels, mechanical energy
	Spinning	Manual spin	Human	Powered spinner	Electricity, fossil fuels, biofuels, mechanical energy
	Packing	Manual packing	Human	Automated packing	Electricity
Crop conservation and distribution	Refrigeration (dairy products, fish, meat)	None	-	Refrigerated storage	Electricity
	Distribution to local market	Walk and distribution with animal	Human and animal	Modern transportation by road	Fossil fuels, biofuels
	Transport to national and international market	-	-	Modern transportation by road, rail, sea or air	Fossil fuels, biofuels, electricity

The productive uses model used to analyze the case study in the Tanga region is a bottom-up, accounting, energy model developed using the Long range Energy Alternatives Planning

system (LEAP). LEAP is a widely-used accounting tool for energy systems and policy analysis, adopted by thousands of organizations in more than 190 countries worldwide [51]. It has the advantage of being a highly versatile tool for energy system scenario analyses¹⁴.

The model explores targeted scenarios for the case study of sisal production in the Tanga region of Tanzania and includes possible impacts of process modernization. These include the adoption of modern technologies both for the income generating activities and for the nearby residential areas or villages. Specifically, they evaluate (1) the substitution of existing, energy-intensive, low-efficiency machinery with energy and water-efficient options; (2) the modernization of agricultural processes, including a new biogas power plant to meet local electricity demand and sell surplus production to the local grid; and (3) combining local productive activities with the generation of electricity and other energy commodities to benefit nearby communities.

The link between the residential electricity model considered in LEAP and the productive uses of energy model opens the way for integrating productive activities energy models in the tool developed in this thesis.

2.3. Focus 3: Generalizable tool for electricity access-and-use

The developed tool¹⁵ is a deliberately simple, excel-based, open-access accounting model that calculates the Levelized Cost of Electricity (LCOE) costs (and total electricity cost per household) for a given timeframe of different electrification options as a function of selected parameters (see Table 5). The tool was developed starting from the electricity access-and-use optimization model developed in the case study section for the considered East Timorese village. However that model had to be significantly simplified. In fact, the optimization model is data intensive with long computational times. Conversely, the final LCOE electrification tool is deliberately simple, both to ensure data availability, and to combine it with geo-referenced studies on a regional and national scale. In such analyses, thousands of settlements have to be evaluated for each result iteration making low data requirements and reasonable computational times crucial for achieving results with manageable delays.

Considered electricity access technologies include a range of both renewable and non-renewable alternatives. Those are further divided among grid connected, mini-grid connected and stand-alone systems. The tool allows a cost comparison of the considered technologies for any combination of the parameters reported in Table 5. That allows the selection of least-cost electricity access technologies for thousands of settlements with low computational times. That permits the tool to be combined with GIS models for national-scale electrification analyses. Resulting solution spaces can be represented both in terms of LCOE and of total

¹⁴ The flip side is that these scenarios are determined by the user thus limiting its applicability to cost optimization or endogenous behavior representation.

¹⁵ Paper V presents the full model parameterization

electricity cost per household for the 2015-2030 timeframe. Chosen for consistency with the SE4All goals, this timeframe is easily modified to focus on shorter or longer periods.

Table 5 Parameters varied in paper V

Parameters	Metric	Value range
Target level of energy access	Multi-Tier categorization of energy access	Tier 1 to Tier 5
Population density	Households/km ²	50 to 650 households/ km ²
Local grid connection characteristics	Distance from closest grid connection point (km)	5 to 50 km
	National cost of grid electricity (\$/kWh)	0.05 to 0.4 \$/kWh
Local energy resource availability and technology cost	Solar Irradiation: kWh/m ² /year	1500 to 2500 kWh/m ² /year
	Wind: capacity factor	0.2 to 0.4
	Mini Hydro: Availability in the vicinity	Available/unavailable within a 10 km radius around the settlement
	Biogas: Feedstock availability (e.g. large-scale livestock farms) in the vicinity	Available/unavailable within a 10 km radius around the settlement
	Diesel: US\$/l	0.5 to 1 US\$/l for mini-grid applications, 1 to 2 US\$/l for stand-alone applications
	Capital cost of generation technologies	Varied by 20% of the baseline cost

The advantage of this simplified approach is its ability to support quick assessments for thousands of electrification projects and provide aggregated local, regional, national, continental and eventually global information. Aforementioned parameters include geographic specificities (e.g. distance from the grid, local renewable resource availability etc.) which can be gleaned from and linked to, amongst others, geographic information systems (GIS). The resulting aggregate information includes technology mixes, capacities and costs. The spreadsheet that the tool it is based on is openly available and was used as a basis of several subsequent studies (See section 4.2 – Impact of the thesis work).

Proving the tool's utility from an operational perspective, such an integration was demonstrated by applying it to three national-level case studies in Nigeria, Ethiopia, and India presented in the results section (these are not the focus of this thesis).

Additionally, this thesis investigated how to extend the scope of the tool for electricity access with considerations on cooking and productive uses of energy access.

The guidelines for the tool application and for the development of similar tools for cooking and productive uses energy access are informed by various sections of all the research work included in this thesis.

3. Results and Discussion

Essentially, all models are wrong, but some are useful.

George E. P. Box, 1987

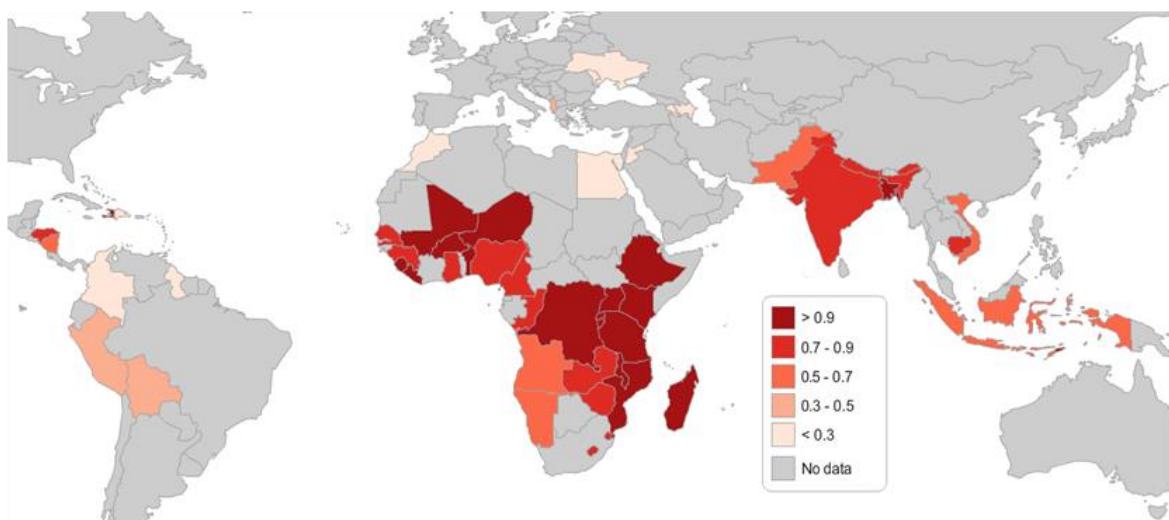
As described in the previous chapters, this dissertation is divided into three interconnected research foci. This chapter is structured accordingly, each section answering the corresponding research questions.

3.1. Focus 1: Measuring energy access-and-use

Energy access planning needs appropriate metrics. Those are needed for both understanding the current energy access status and the success of past programs, and to plan future energy access plans. This thesis found that currently there is not a single metric that can address both needs. Therefore, two metrics are used, the MEPI for the first need, and the World Bank Multi-Tier framework for the second.

In Figure 6 country results for the MEPI are reported. The index appears useful for cross-country analysis. The countries are classified according to the degree of energy poverty, ranging from countries with acute energy poverty (MEPI > 0.7), to countries with low degree of energy poverty (MEPI < 0.2).

Figure 6 The Multi-Dimensional Energy Poverty Index, country results



Additionally, results of the MEPI country analyses can be disaggregated in several ways including cross-country, high-level and composite indicator level comparisons. For instance (Table 6), considering results for selected countries we notice that in Madagascar, despite the fact that the overall MEPI is much higher than in Zambia, the electrification rate is comparable. This means that Madagascar performs much worse in other indicators, e.g. access to modern cooking. Similarly, Lesotho is significantly better off than Zambia in terms of energy poverty, but features an electrification rate that is notably lower than Zambia. One other interesting way to look at MEPI results is the cross-country comparison of headcount ratio, ratio of energy poor people, and energy poverty intensity in the country. Given countries show that, although more people may be considered ‘energy poor’ (i.e. have a higher headcount ratio H), the ‘intensity’ of their energy poverty (A) is lower.

Table 6 Comparison of energy poverty and selected indicators¹⁶

<i>Country</i>	<i>Year</i>	<i>H</i>	<i>A</i>	<i>MEPI</i>	<i>Electrification rate</i>	<i>Modern cooking rate</i>
Namibia	2006-2007	0.66	0.72	0.47	39%	35%
Lesotho	2009	0.84	0.64	0.54	16%	34%
Nigeria	2008	0.79	0.71	0.56	48%	21%
Zambia	2007	0.87	0.78	0.66	21%	16%
Sierra Leone	2008	0.97	0.75	0.73	11%	0%
Malawi	2010	0.97	0.79	0.77	9%	2%
Madagascar	2008-2009	0.98	0.81	0.8	17%	1%

Additionally, DHS surveys are available over several years making it possible to trend MEPI calculations over time. Such an analysis, can, in turn, help understand energy poverty trends. For instance, MEPI trends show that even if the amount of ‘energy poor people tends to remain constant in a number of sub-Saharan countries, the intensity of energy poverty consistently decreases in all analyzed countries. This seems to show that the MEPI is valuable for overcoming simplistic consumption or access indicators, while tracking energy access-and-use with available data across several countries¹⁷.

However, built on the basis of existing non-energy focused datasets, the MEPI appears both limited for applications to bottom-up energy modelling work, and unable to support optimal resource allocation in energy access-and-use planning. Specifically, the MEPI lacks the technical detail required for bottom-up energy modelling. It considers only a fraction of household energy needs (e.g. the appliance ownership categories only include fridges, radios and televisions). While a useful proxy for evaluating energy access-and-use trends with available statistics, the household energy needs considered in the MEPI are unfit for supporting technology-rich modelling efforts. Therefore, the extended MEPI analysis, more

¹⁶ Color code: light blue: better; dark blue: much better; light red: worse; dark red: much worse

¹⁷ Further MEPI country results and additional index analyses are detailed in paper I.

than simply instructive, fills the monitoring gap while lacking the technical handle required to combine it with bottom-up energy modelling.

On the other hand, the World Bank Multi-Tier approach cannot currently be used to analyze the status and progress of energy access-and-use in energy poor countries: created recently, it lacks country level detail and large scale surveys. Instead, the Multi-Tier approach structure and potential future applications make it compatible with detailed technical energy modelling efforts subsequently developed in this thesis. This thesis does not develop the Multi-Tier framework. However, it applies it (innovatively) for supporting the energy access-and-use quantified studies presented in the next sections of this thesis.

3.2. Focus 2: Local case studies results

3.2.1. Case study 1: Comparing Rural Electrification Options in The Brazilian Amazon¹⁸

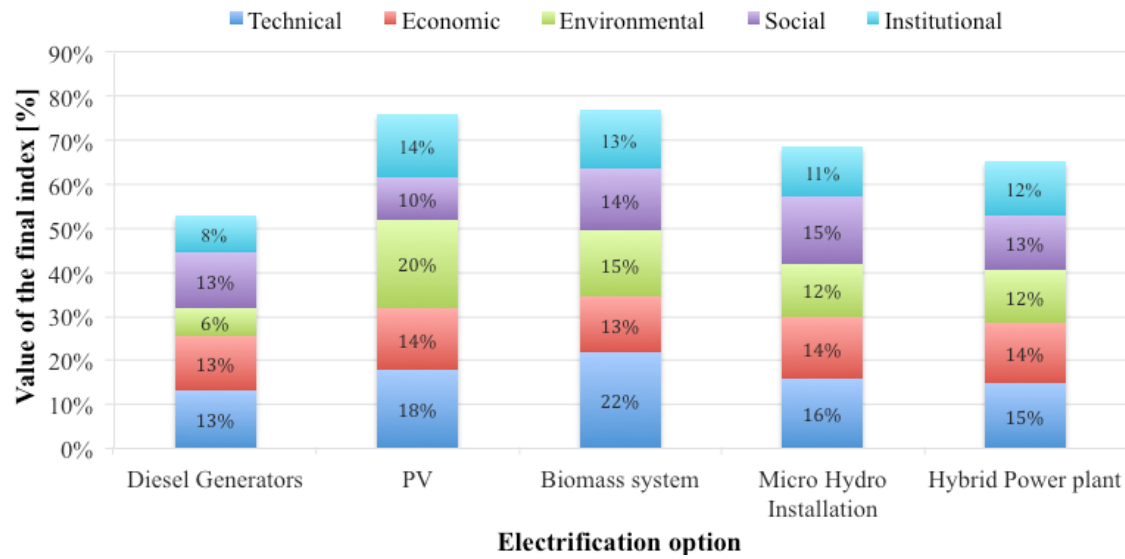
The case study results help contextualize the current energy access situation in the Brazilian Amazon while at the same time providing insights on the criteria to be considered when choosing among electrification options. In Brazil, thanks to the governmental program ‘Luz Para Todos’ (LPT), more than 14 million people received access to electricity through grid connections [52]. Nevertheless, grid extension in the Amazon region is, in many cases, no longer an economically feasible option due to both long distances between the communities and the grid, and a relatively challenging topography. As a result, and although many communities in the region were electrified using diesel-powered mini-grid and stand-alone solutions, it is estimated that almost 1 million people still lack access to electricity services [53].

A first result from this case study is the assessment of the relative importance of the considered criteria in the decision making process among energy access-and-use options. Results from the semi-structured interviews with local stakeholders show that the highest weights were given either to the Economic or the Technical criteria with a focus on the costs (O&M and capital) the resource availability and the reliability sub-criteria. Although criteria considered in the Amazon region may not be representative of other areas and may have neglected some aspects of the decision making process, they confirm the importance of considering techno-economic aspects in energy access-and-use policy analysis (also underlined by the World Bank in [54]). With this in mind, the other case-studies presented in this thesis and the final tool concentrate on analyzing techno-economic aspects of the comparison between energy access-and-use options.

Additionally, the MCA helps contextualize the fact that the best scoring solutions in terms of techno-economic and environmental criteria are not being adopted in the region (Figure 7).

¹⁸ The detailed results of the multi-criteria analysis, including the comparison of the single technologies and a sensitivity analysis of the results, are reported in the appended paper II.

Figure 7 Values and structure of the final aggregate index of the MCA



In fact, of the five electrification solutions that were compared, diesel fueled power solutions present drawbacks under most of the criteria. This technological option offers the worst results when graded with all of the technical, environmental and institutional criteria and comes second to lowest in the economic and social criteria. For instance, looking at the cost criteria fuel cost is a large concern. In fact, transportation of fuel to remote locations may take several days by boat [55]. The result is that the cost of diesel for isolated communities, once the transportation costs are considered, may be two or three times greater than prices charged at gas stations [56]. Nevertheless, diesel-fueled solutions are currently the most adopted solution for off-grid electricity access in the region. Further investigation of the ranking criteria for diesel-powered solutions shows that they have, in fact, been adopted mainly due to the key advantages they present for the concessionaries. These systems are the most convenient short-term solution for trying to meet the LPT program universalization targets within short governmental deadlines. Also, in the Amazon region, these diesel systems are a well-known technology, with low capital costs and a consolidated fuel and system maintenance supply chain. Yet concessionaries have failed to take into consideration the high fuel costs. Thus an economic trade-off exists between the high operation and maintenance costs of diesel systems in the long term, and the costly fines that are applied to the concessionaries that do not reach LPT connection targets in the short term. It appears therefore that there is a policy failure (governance/informational), which tends to generate a sub-optimal energy use pattern while distorting the energy user's choice [57]. To overcome that, institutional structures need to be adapted to deliver local-resource based technologies [53].

Finally, this case study is useful for contextualizing some of the aspects that have to be taken into account for the application of the least-cost energy access-and-use tool in the planning process.

3.2.2. Case study 2: Estimating the cost of energy access in rural Timor Leste¹⁹

Building on some of the techno-economic sub-criteria explored in the Brazilian Amazon case study, this case study develops a rural energy model comparing electrification and cooking options for the Suro Craic village in East Timor. Suro Craic is medium size rural village of approximately 350 households, in the district of Ainaro [58] in the southwest part of the country. It is one of the least developed districts in Timor-Leste, and thus useful for exploring potential movement through all Tiers of energy access. The village has no grid connection and only a small share of its population has some form of electricity access with stand-alone PV or small diesel generators, mostly operated by local entrepreneurs. An open fire is the main cooking method for virtually all households.

Emerging from the electricity access-and-use analysis, a set of parameters that influence the cost of electrification technologies was used to support the tool presented in the last part of this dissertation. They include:

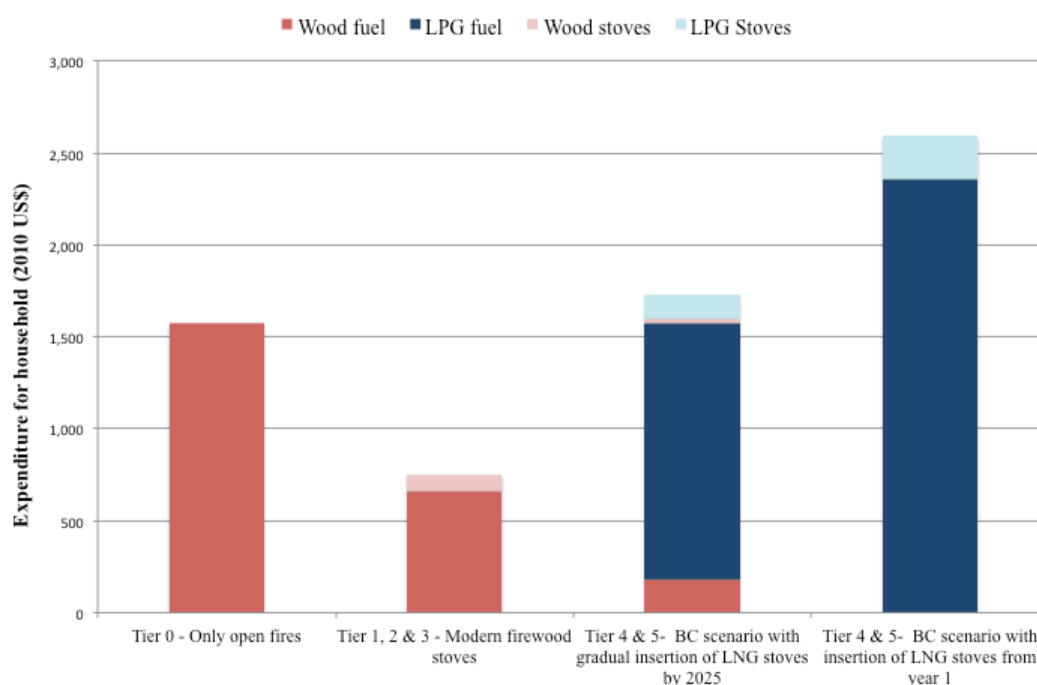
- The target level of energy access: that influences both total electrification costs and technology choice. Model results for the considered village show, for instance, that achieving the highest tier of electricity access in the period 2010-2030 could be as much as seventy-five times costlier than achieving the lowest one. In addition, moving across electricity access tiers, least cost solutions shift from stand-alone to mini-grid and finally grid connected options as electricity access increases.
- Population density: influences the number of households in the village and thus the overall energy demand. The vicinity of the households and the energy demand per household influence the cost per unit of electricity of grid-based technologies. As a result, increasing population density influences the cost of electrification and the technology choice.
- Local grid connection characteristics: In the case study the grid connection is located at approximately 10 km from the village. The cost of grid electricity varies between 0.15 and 0.4 USD/kWh in Timor Leste. In this context both the cost of electricity from the grid and the distance of the village from the grid connection point, influence the economic viability of the grid option.
- Local availability of energy resources and technology cost: can differ significantly from one region to the next depending, among others, on specific geographical location, existing supply chains or government subsidies. Most of the results for the village case study can therefore not be generalized to other villages, even when considering villages located in the same country.

Several lessons can be learned from the model comparing cooking solutions, which could be used for the future integration of cooking access into the tool developed in focus 3. Key among them are:

¹⁹ Full scenario analysis and model assumptions are reported in paper III appended to this thesis

- The importance of defining the target level of cooking energy access for the final costs and technology choice. In this context, while improving access to electricity services generally results in a cost increase, some improvements in cooking access result in cost savings. In fact, moving from open fires to some of the more modern solutions has the potential to reduce overall costs over the model period (Figure 8). Adopting improved cooking stoves, could potentially reduce total cooking costs per household by approximately half with respect to a Tier 0 situation (open fires cooking). On the other hand, For Tiers 4 & 5, where only cooking solutions using modern energy fuels or electricity are allowed in the model, costs are considerably higher and depend on the speed of adoption of the modern cooking solution.

Figure 8 Estimated total cost for household in the years 2010-2030 for different cooking tiers of access in the rural village of Suro Craic (All technology and fuel costs as in the Base Case (BC) scenario presented in paper III appended to the thesis)



- The significance of local resource availability and costs for the comparison among cooking solutions. Local LPG and electricity cost as well as corresponding reliability of supply strongly influence the cost competitiveness of modern cooking solutions.
- The availability of local wood (and charcoal) and its impact on the sustainability of final cooking solutions. In the considered village, the continued use of open fire cooking could potentially deplete the local forest. In fact, the estimated sustainable consumption of wood (see paper III for the calculations) in the surrounding area is only sufficient to provide for approximately 90% of wood requirements in 2010, and 65% in 2030 if all cooking continues being done with open fires.

Although not developed further in this thesis, there is thus scope for simplifying the cooking cost model and developing it into an analytical tool such as the one presented in this thesis for electricity access. Guidelines on how to do so are presented in Section 3.3.2 of this thesis.

3.2.3. Case study 3: Powering the agricultural production in the Tanga region, Tanzania²⁰

Finally, this case study complements the previous ones focusing on the relation between productive activities and energy access-and-use. It discusses the importance of facilitating energy access for productive activities as both a means to improve livelihoods in the poorest countries, and a driver of economic development.

It focuses on the sisal fibre production activities in the Tanga region, where most of the Tanzania's sisal is produced. Sisal production is labor, energy and water intensive, with energy representing from 30% to 45% of the cost of production. In several estates lack of a reliable electricity and fuel supply is a fundamental bottleneck to production and limits productivity.

One first outcome from the case study is that addressing productive uses of energy for a diverse set of activities, each characterized by different energy needs, calls for the development of several sector-specific models. Even when looking at the same sector, for instance agriculture, the type of agricultural crop and practices can change both the total amount of energy consumed as well as the proportions of energy used for various inputs [59].

Second, results reveal a large margin of improvement in energy efficiency and energy production gained from several costs-effective and possibly environmentally-friendly actions. Modernization of the energy system could result both in decreased expenditures and increased incomes for the productive activities. Electricity and diesel, in fact, represents over 40% of the considered agricultural production costs. The energy efficiency scenario analysis shows how, even by intervening only on the most energy-intensive production processes, electricity use could be reduced by 70%, diesel use reduced by one third, and water use and greenhouse gases emissions reduced considerably. The productive uses scenario combined with the energy for all scenario analysis shows how locally produced electricity, fueled by production residuals, has the potential of sustaining the electricity needs of all the communities living within 5 km of the estate's agricultural activities up to a Tier 4 of residential electricity access. Additionally, electricity could be produced at a lower cost than that of local grid electricity or of locally owned diesel generators. Finally, residuals from the production of biogas could potentially be used to fertilize local agricultural production, thus increasing agricultural yield.

Therefore, considering productive activities in electrification planning can potentially result in a number of win-win-win solutions for the local utilities, the companies and the local

²⁰ Detailed scenario analyses and results are reported in paper IV appended to this thesis

residents. In cases in which productive activities can be combined with power production, local utilities could diversify their generation portfolio and distribute their power with the support of small local producers. Through better management of both energy use and production, the companies could see a decrease in the energy expenditures, an increase in productivity and a diversification of their business. And finally, the local population could benefit from an increase in electricity access provided from a reliable local supplier.

This case study presents a first attempt at integrating a productive activity sector (agriculture) into an electrification tool. Also, it opens the way for developing a location-specific methodology for better integrating productive activities in the tool presented in focus 3 of the thesis, and more broadly in electrification planning.

3.3. Focus 3: Tools to evaluate technology and costs trade-offs for achieving useful energy access-and-use goals

3.3.1. The tool for electricity access-and-use²¹

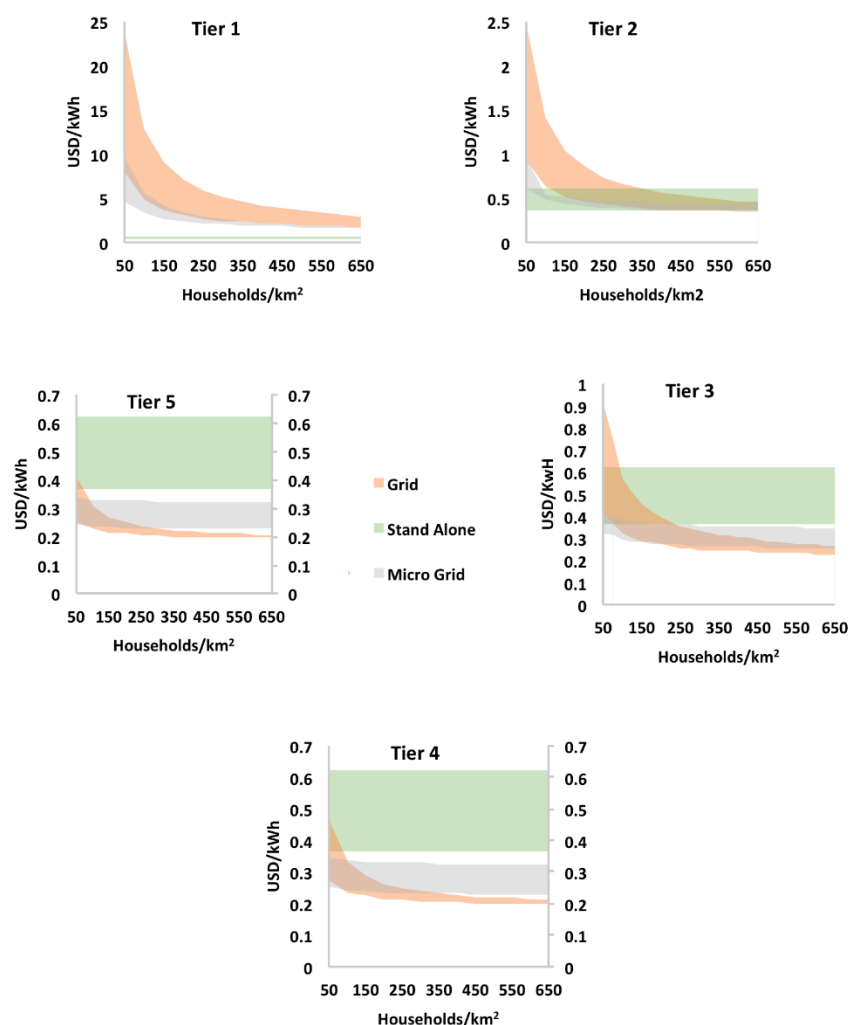
Drawing information from all the previous sections, this section presents a simplified tool for the cost comparison of different electrification technologies. It includes a least-cost electricity access model and a series of guidelines for its usage to inform electrification planning.

The model is based on the four parameter families characterized in the East Timor case study, namely (i) target level and quality of energy access, (ii) population density, (iii) local grid connection characteristics and (iv) local energy resource availability, fuel and technology cost. Varying the values of the those parameters in the tool a large spectrum of least-cost solutions can be found, showing, once again, the value of considering locally-bounded characteristics for electricity access planning. The next paragraphs discuss key considerations relating to this final electrification tool.

The target tier of energy access helps to understand potential cost benefit implications of different energy access projects. For instance, the cost of achieving a Tier 5 – high level – of energy access can be 50 to 100 times larger as compared to a Tier 1, depending on locally available energy sources. Additionally, the use of structured targets illustrates the difference between situations requiring grid-connected, mini-grid and stand-alone solutions (Figure 9).

²¹ The parametrization of the model is presented in paper V along with its applicability for supporting GIS-based electrification studies.

Figure 9 LCOEs of providing energy access with grid, mini-grid and stand-alone technologies²²



At higher tiers of energy access, it is noticeable that stand-alone solutions become costlier as compared to other solutions, both per kWh and in terms of total cost per connected household. Higher energy requirements make the transmission and distribution investments more economic on a cost per kilowatt basis. As a result, both the least-cost split among grid-connected, mini-grid and stand-alone solutions, and the final cost of the electrification program change substantially with different targets of energy access.

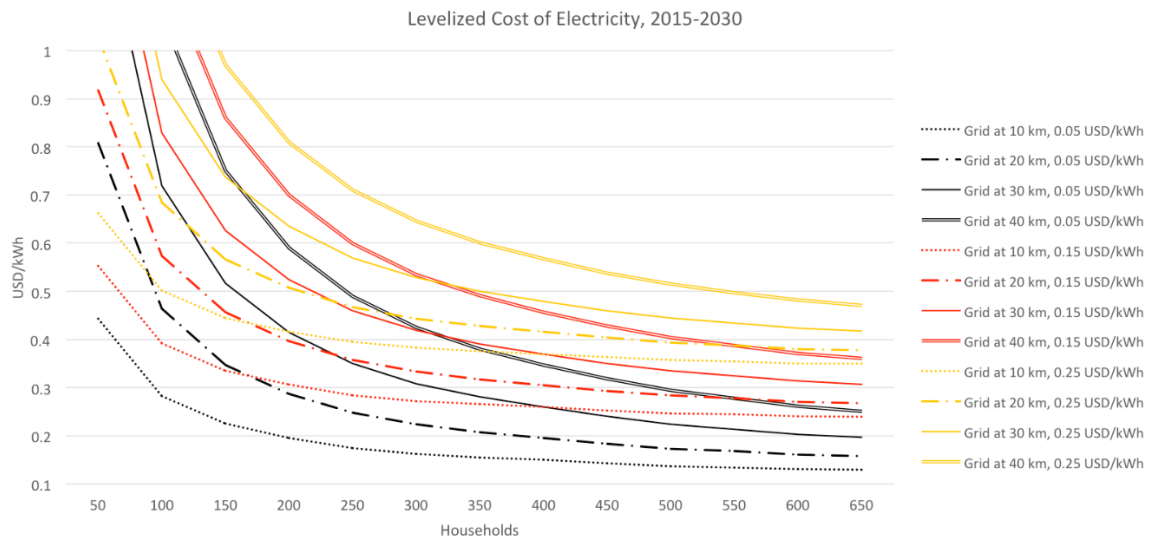
²² Technologies included:

- 1) GRID: Grid connection in between 5 and 20 km of distance, with a national grid electricity price of 0.15 USD/kWh
- 2) MINI-GRID: Diesel MG with a Diesel price of 0.5 US\$/l, Wind energy based MG with Capacity factor (Cf) =0.2, PV based MG with Irradiation between values of 1500 to 2500 kWh/m²/year;
- 3) STAND-ALONE: Diesel based SA solutions with Diesel prices between 1 & 1.5 US\$/l , PV based SA solutions with Irradiation values between 1500 and 2500 kWh/m²/year

Second, the size of the settlement to give energy access to or, correspondingly, the population density when considering large areas, is also a key parameter for electrification analyses. In general, higher population densities provide a higher population basis to share the grid transmission and distribution costs. As a result, grid and mini-grid based solutions become more cost competitive compared to stand-alone solutions with increasing population densities.

Third, local conditions and characteristics of the national grid will affect the choice of grid or off-grid solutions. Figure 10 shows these dynamics for selected combinations of electricity costs and distance to the grid connection point. On the one hand, the distance from the closest connection point to the national grid as well as the grid electricity cost directly influence the final cost of newly electrified settlements. On the other hand, local grid electricity characteristics impact the quality and reliability of grid electricity supply. Additionally, local grid electricity provision in energy poor countries may be characterized by frequent power cuts [5] giving locally powered stand-alone and mini-grid solutions a significant advantage in terms of reliability²³.

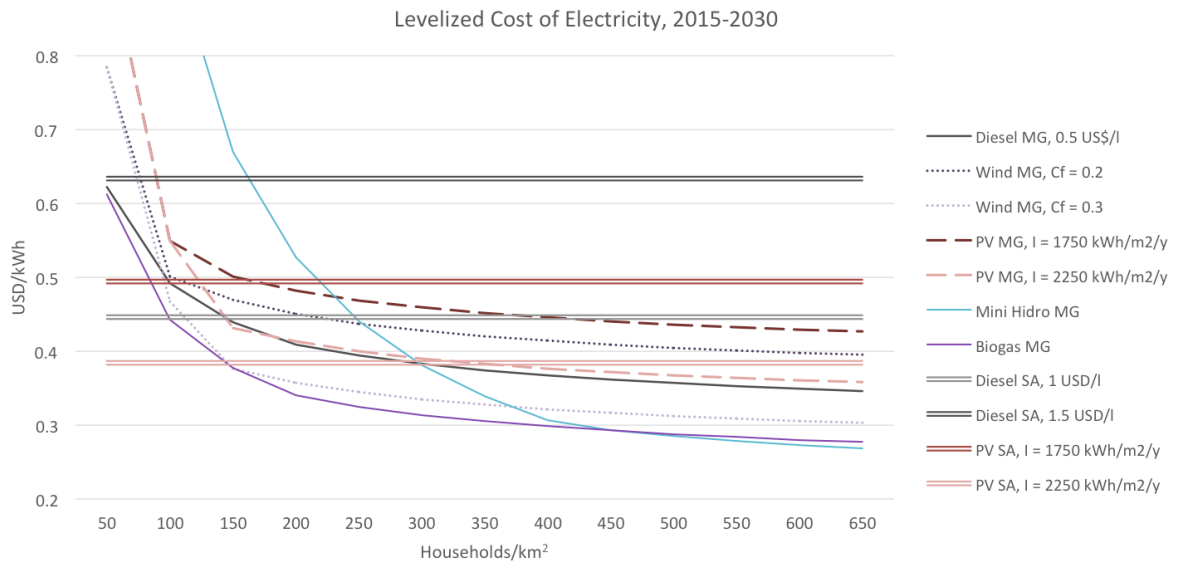
Figure 10 LCOEs and total costs of energy access per household under different grid connection characteristics, Tier 3 of electricity access. (For each distance the LCOE is calculated using three different unit costs of electricity)



²³ For computational simplicity, the model presented in this dissertation considers a simplified model for grid electricity: the supply of grid electricity is represented as a ‘black box’ providing electricity at a certain cost and with a certain reliability. In order to take into account a thorough representation of national grid electricity supply characteristics, future work could combine the electrification tool with traditional energy planning models. Such models have been applied to analyses in energy poor regions including African power pool modelling efforts (such as [70] [71]), the Electricity Model Base for Africa (TEMBA) [73], the country- and continent-scale modelling presented in the Africa Energy Outlook of the International Energy Agency [6], or the impact assessment of the Grand Inga dam on the Central African power pool [72].

The local resource availability and technology costs have a direct influence both on the final cost of electrification projects and on the choice of technology. Large regional availability of renewable energy sources, such as solar, wind, biomass or hydro, can shift the decision process significantly towards using higher amounts of renewable energy technologies. At the same time, the combination of local fossil fuel costs with the distance between its supply and consumption points have a significant impact on the competitiveness of fossil-fuel powered solutions. Figure 11 shows the comparison between selected mini-grid and stand-alone technologies, as a function of energy resource availability and fossil fuel costs.

Figure 11 Cost comparison of selected stand-alone and mini-grid technologies with Tier 2 of energy access target



Finally, the tool was tested with several national-scale electrification studies. Results for the country cases studies of Nigeria and Ethiopia are reported in Figure 12. Also, Figure 13 represents how the least-cost surfaces represented in Figure 12 can be applied to GIS models. The methodology used to integrate the cost model presented in this dissertation into GIS models is described in [60]. Note that GIS models are not the focus of this thesis, however Figure 13 indicates the hypothesis that the simplified tool has utility in national-scale GIS electrification studies.

Figure 12 Nigeria (top) and Ethiopia (bottom). Left: least cost LCOEs as a function of the distance to the grid and population density. Right: consequent number of connections and overnight investment for each connection type (right). Stand-alone options are represented in purple, mini-grid options in green and grid options in blue

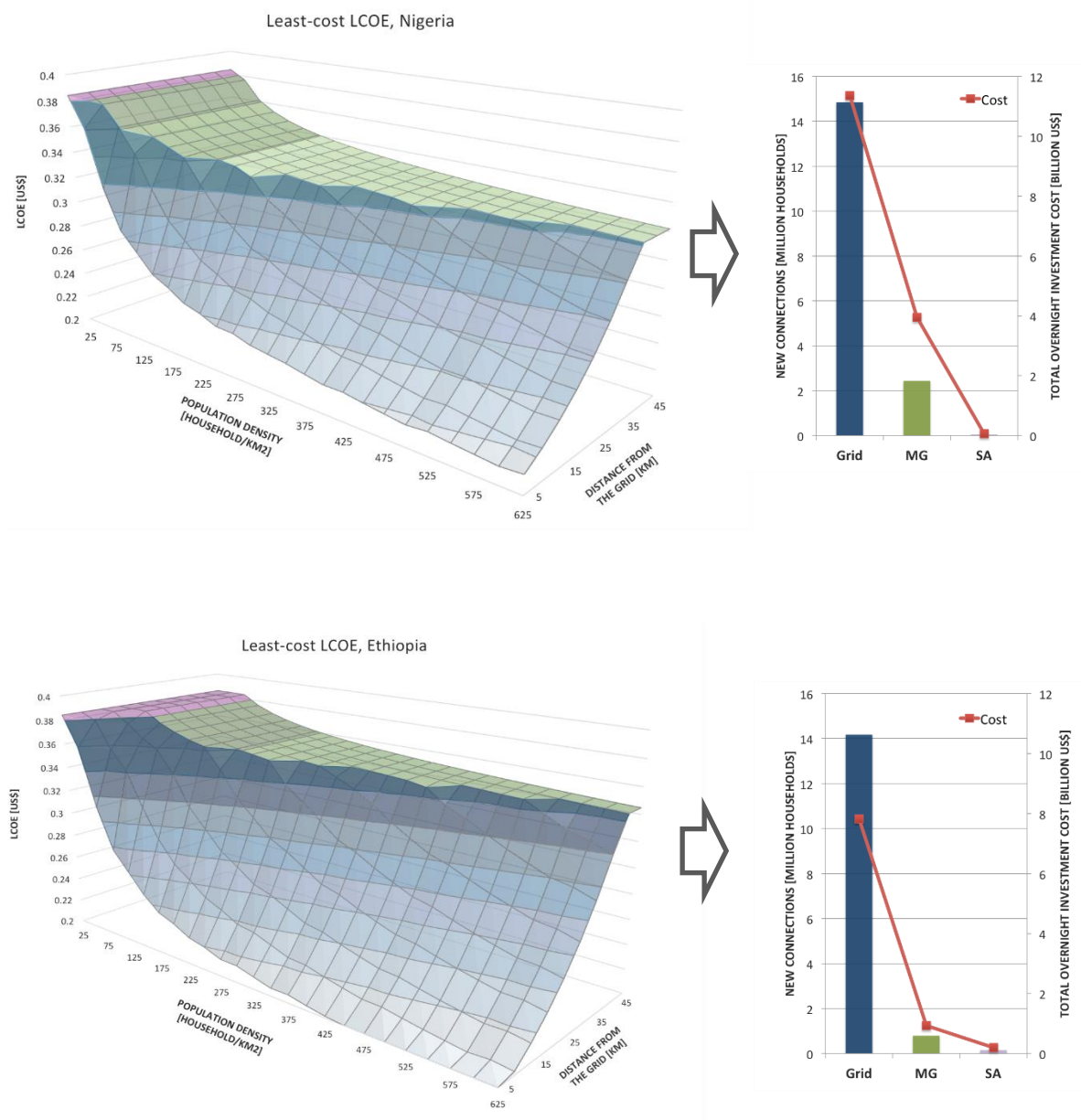
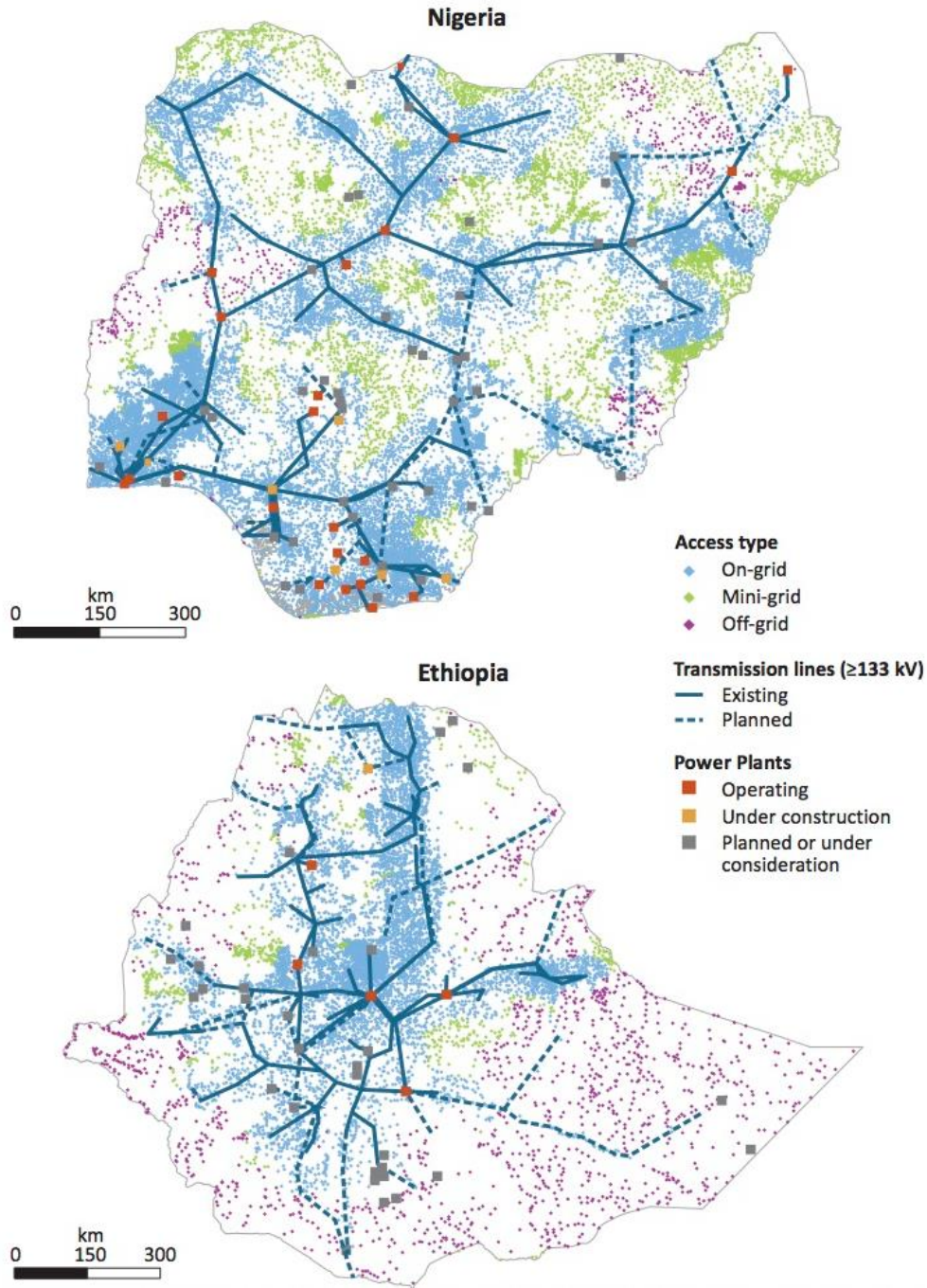


Figure 13 Optimal split by grid type in Nigeria and Ethiopia, based on anticipated expansion of main transmission lines, as featured in the IEA World Energy Outlook 2014 [31]

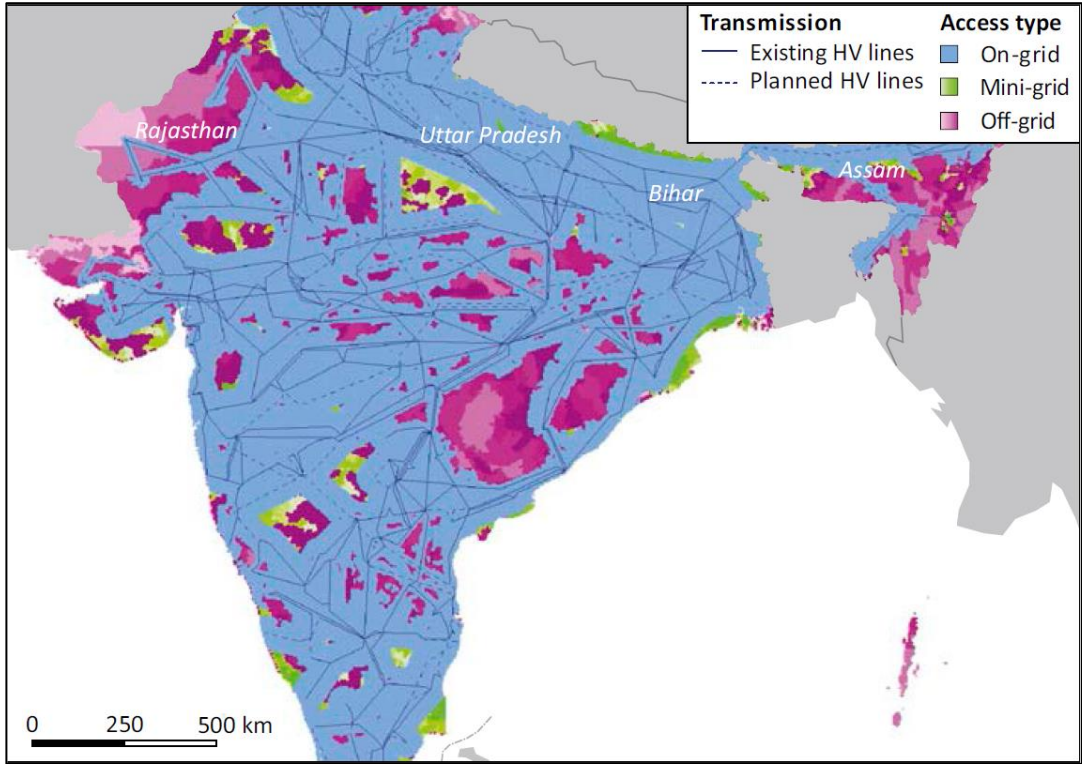


The left hand side of Figure 12 represents the country-specific surface of least-cost electrification options for Nigeria and Ethiopia as a function of population density and settlements' distance from the grid. This image shows the split of least cost solutions between grid, mini-grid, and stand-alone options. The surface of solutions, when applied to each of the two countries' settlements, enables the analyst to extract investment requirements such as the ones represented in the right hand side of

Figure 12, as well as the geospatial analyses reported in Figure 13. In the two African countries considered, given the electricity access-and-use target, grid-based solutions proved to be the least-cost option for most of the newly electrified households (approximately 85% of the households in Nigeria and 93% in Ethiopia). Nevertheless, both countries also rely significantly on mini-grid and stand-alone solutions, which prove to be cost effective in providing electricity access for large areas with low population density. Comparing the two countries, results show how, in rural Ethiopia, a lower population density would favour stand-alone solutions for providing energy access to large areas of the country. In Nigeria, however, higher population densities result in a higher share of mini-grid solutions over stand-alone solutions. Note that these results were calculated based on the target of energy access determined by the IEA’s New Policies Scenario [6]. Different access targets would result in different splits between grid and off-grid solutions.

The tool was also applied to a national-scale case study for India. The results for India (Figure 14), relevant for access targets specified in the IEA’s Indian Vision Case [32], also show the combination of technologies that could be used to reach energy access goals cost-effectively. Of the 240 million people without access today, around 25% gain access via the grid, 35% via mini-grid systems and 40% via off-grid systems. The higher share of new connections achieved with off-grid solutions, compared to the country cases of Nigeria and Ethiopia, is mostly due to the fact that in India the areas that are still un-electrified are the so called ‘last-mile’ in the electrification process. These are the areas that are usually the most costly to reach with the grid due to factors such as geographical conditions or low population densities. Nonetheless, on-grid connections still remain the dominant type of electricity connection in India in 2025.

Figure 14 Optimal split by grid type in India, based on anticipated expansion of main transmission lines, as featured in the IEA World Energy Outlook 2015 [32]



3.3.2. Guidelines for the future development of cooking and productive uses energy access tools

Although the case studies investigated access to electricity, cooking and energy for productive activities, the tool presented in the thesis looked only at the provision of electricity. However, the case studies offer a starting point for including cooking and productive activities in similar tools to the one developed in this thesis for electricity access.

Similarly to the electricity access model, the optimization of cooking energy access model presented in the East Timorese village case study could be simplified computationally and enriched with more technological cooking options for increasing its applicability. Doing so would permit its usage to be combined with GIS models. Such a simplified model to compare cooking options could be parameterized to broaden its applicability and to better represent the location-specific system costs. In the following paragraphs some key parameters are suggested for the creation of such a tool.

The first parameter to consider is the target level of cooking energy access. This thesis suggests the usage of the World Bank's Multi-Tier framework for cooking energy access [5] in combination with the International Organization for Standardization (ISO) standards for cook stoves proposed in the International Workshop Agreement (IWA) 11:2012 [61]. These are the leading metrics used for tracking access to cooking solutions. The two scales are comparable, and the combination of the two is reported in Table 7.

Table 7 IWA standard 'Tiers' and WB 'levels' of cooking energy access. Elaboration of the author from [5] [61].

IWA standard	World Bank GTF level	Cookstove and fuel	Efficiency (%)	Indoor pollution (CO - g/min/l)	Indoor pollution (PM - mg/min/l)	Safety
Tier 0	Level 0 or 1	Self-made cookstove	< 15	>0.97	> 40	poor
Tier 1	Level 1 or 2	Manufactured non-BLEN ²⁴ cookstove	≤ 15	≤ 0.97	≤ 40	poor
Tier 2	Level 2 or 3		≤ 25	≤ 0.62	≤ 17	fair
Tier 3	Level 3 or 4	BLEN cookstove	≤ 35	≤ 0.49	≤ 8	good
Tier 4	Level 4 or 5		≤ 45	≤ 0.42	≤ 2	best

²⁴ BLEN = refers to cook stoves that uses one of the following as fuel: Biogas, LPG, Electricity or Natural Gas

Other cooking-medium specific parameters to be considered in the cost comparison would be:

- Stove investment cost
- Stove operation and maintenance costs
- Stove lifetime [years]

Also, another parameter to consider would be the local resource availability and cost. For fossil fuels-based cooking solutions this would be the local cost of purchasing the fuel and its local availability. For electricity-based cooking solutions this would be the availability of electricity (e.g. grid connection) on the site and its cost. This part could be linked to the tool for electricity access presented in the previous section. For firewood, depending on its source, it would be either the cost of purchasing the firewood or the opportunity cost of collecting it. In the case of collected firewood, local availability (and sustainability of collection) would be another important parameter.

In such a cooking access tool cooking solutions could be then compared based on their lifetime costs or on a ‘levelized’ cost that could be reported either per meal or per day.

Powering economic activities could be considered in several ways in similar tools. One simplified option for electricity-intensive productive activities would be the addition of a demand to the settlements electrical demand in the electricity access-and-use cost model. Different loads could be calculated depending on the productive activity. Doing so, it would be possible to evaluate the effect of different productive uses on the local electricity system.

A more thorough approach would be to develop, for all rural productive activities sectors, cost-technology models similar to the one presented in the Tanga case study (Paper IV). This effort would enable the analyst to consider not only electricity inputs to productive uses but also any other energy input. Doing so, it would enable the representation of more complex interactions between energy access and productive activities. However, this effort would require significantly more complexity. In fact, each productive activity sector would require a dedicated tool.

3.3.3. Other guidelines for the application of the developed analytical tool

Additionally, the following insights and guidelines for the application of the analytical tool (and more generally for the application of quantitative models in energy access planning) can be drawn from foci 1 and 2 of the thesis. Far from an exhaustive list, it is intended rather as a compilation of lessons learned during this thesis work for applying least cost models in energy planning.

i. Energy access-and-use targets should be as detailed as possible

The importance of setting as detailed energy access targets as possible in the energy planning efforts is continuously underlined in this dissertation, and the implications of setting different access targets are presented in papers III, IV and V. This dissertation suggests the usage of the World Bank's Multi-Tier framework for setting the targets of energy access-and-use, for the reasons underlined in section 3 of this thesis.

ii. A mix of technologies will be needed to achieve national energy access-and-use goals in a least cost manner

As seen in both focus 2 and 3 of the thesis, least cost technologies for electrification, for cooking and for providing energy for productive uses vary greatly with local characteristics, and therefore within and among countries. As a result, a mix of technologies have to be taken into account so as to lower the costs of energy access-and-use. Promoting a single technological solution (e.g. only grid connection or only stand-alone electricity access solutions) at a country scale might result in increased costs. The tool provided in this thesis supports the selection of electrification technologies depending on locally-bounded characteristics.

iii. Adequate policy analysis and formulation are needed to support the adoption of locally adequate electrification solutions

Analytical tools such as the one presented in this thesis can be useful for comparing energy access solutions. However those have to be framed in the local policy context. For instance, the Brazilian Amazon case study shows the significant influence of national policies on the adoption of one technological solution or another. Specifically, it revealed that the institutional setting promoted the use of cost-, environment- and health- ineffective electrification solutions. Further, high institutional barriers for the entrance of new power producers undermined the development of a market that might provide electricity services in rural areas. A key lesson can thus be drawn from this study: optimal resource allocation models, combined with the evaluation of other criteria such as social and environmental impacts, can help policy makers to see system inefficiencies and to create cost-effective and sustainable electrification plans. To do that, cost models have to be combined with the analysis of current local energy policies to identify existing barriers for the adoption of cost effective and sustainable electrification solutions.

iv. A range of players and funding options will be needed to achieve electrification goals cost-efficiently

This was repeatedly seen in this research work. The Brazilian Amazon case study shows the potential benefits of policy support when creating enabling environments for new players that may provide rural electrification services more effectively than the public sector, either selling electricity to the grid or directly to new customers. An example is presented for the case of the sisal production in Tanzania, where new power producers are able to sell

electricity to the national grid or directly to the costumers with well-established power purchase agreements.

In parallel, effective schemes that provide targeted credit and subsidies can help speed up the adoption of efficient and cost-effective technologies. Examples include supporting energy efficiency measures and power production in certain productive activities (Paper IV), or speeding up the switch from harmful and costly energy-related practices illustrated by e.g. open fires vs. modern cooking solution (Paper III). Additionally, access to financing schemes that reduce environmental externalities could effectively provide another source of income for new power projects. Funding for such interventions could come, for instance, from international climate financing like the Nationally Appropriate Mitigation Actions (NAMA) [62], or the Clean Development Mechanism program [63]. Additionally, the Reducing Emissions from Deforestation and forest Degradation (REDD) programme [64] could support interventions that benefit forest coverage: for instance, carbon financing could play a key fostering role for local, low-carbon power generation in the case of sisal production activities in the Tanga region.

v. Considerations at the local/project level should complement cost based national- or regional- level energy planning

National or regional centralized energy access planning, which might be informed by tools such as the ones developed in this dissertation, have to be harmonized with local conditions. For instance, the Brazilian Amazon case study shows the importance of planning and promoting energy systems that are not only based on cost factors but are also appropriate for the local context. For instance, areas where the availability of skilled labour is an issue might favour systems with low operation and maintenance needs.

Additionally, the scalability of the energy system should be taken into account in electrification planning. Systems that are scalable can adapt to growth in electricity demand and thus ensure that the choice of technology will not limit future local electricity needs. This consideration applies both to scaling up a single technology (e.g. over time, from a n kW to an $(n+m)$ kW stand-alone PV system) and to integrating the existing system with other technologies (e.g. over time, from a first installation of a stand-alone PV system, to its integration within a mini-grid, and further to the mini-grid's inclusion in the national grid system).

vi. Considering productive activities in electricity access and use planning can provide economic and operational benefits.

As seen in the case study of the sisal production in Tanzania, the inclusion of productive activities in electrification planning may result in a number of win-win-win solutions for local utilities, producers and local residents. Also, in the Brazilian Amazon case study the 'Support to local productive activities' and 'Job creation' criterion play an important role in the selection of electrification technologies. Finally, systems that can be used in conjunction

with local productive activities (e.g. electricity production in conjunction with vegetable oil extraction from local Amazon forests) present several co-benefits over other options.

This thesis presents a first attempt at connecting a electricity access tool with productive uses, and there is a scope in further developing this aspect in future work.

- vii. Coordinating energy policies with agricultural, water, environmental and broader economic policies is key

The case study of the sisal production in Tanzania shows how a ‘nexus’ [65] approach, looking in parallel at different resources, could benefit energy planning. In that case study, a more efficient use of energy could result in reduced water requirements, increased agricultural productivity, reduced environmental emissions, and increased rural incomes. Also, model results from the East Timor case study shows how the wood usage for cooking services relates to the local forest availability.

In this context, the need for cross-sector policy integration is confirmed repeatedly in the literature. Among others, the SE4All Global Tracking Framework 2015 report dedicated a full section to cross-cutting issues²⁵, exploring the cross-sectoral issues of energy, water, food, health and gender [13]. The importance of and strategies for integrating climate change, land-use, energy and water strategies was underlined in [66]. Additionally, a recent study by the World Bank combined agriculture, hydrological, energy and climate modelling to explore these different systems’ climate vulnerability [67].

- viii. Adequate local capacity is needed to produce energy access-and-use plans, secure the funding to translate them into action, and maintain a functional energy system

The tool developed in this thesis was especially designed to reduce adoption barriers for analysts in low- and middle- income countries. Still, capacity building efforts are essential on two levels. First, for analysts and policymakers that create and carry out energy plans. Specifically, local capacity is necessary to assess and select locally appropriate solutions. Second, for the people that will operate and maintain the physical energy system.

²⁵ To which the author of this thesis contributed.

4. Conclusion, limitations, proposed future research and impact

*"Achieving sustainable energy for all is not only possible, but necessary.
It is the golden thread that connects development, social inclusion and environmental
protection"*

United Nations Secretary-General Ban Ki-moon, New York, 2012

This chapter presents conclusions for this study, together with the impact that the work presented in the thesis has had and potentially will have in the future. Some of the limitations of the work presented in this dissertation are presented, together with a discussion of possible future research.

Achieving Sustainable Development Goal number 7 and the Sustainable Energy for All goals will be challenging both on the global and on the local scales. Governments and practitioners will need analytical tools to support their energy access planning process. Accordingly, this thesis develops a tool for comparing electrification options together with a series of guidelines for funding allocation and appropriate technology approach selection for energy access. Further, it opens the way for including productive uses of energy and cooking energy access models in subsequent modelling efforts.

Although a limited piece of a complex energy access puzzle, the work presented in this dissertation provides indications to help policy-makers choose between electrification technologies. First, it presents a deliberately simple, open access, tool for the cost comparison of technologies for electricity access-and-use, applicable both to fast assessments of specific energy access projects, and to larger regional studies using a geo-referencing software to analyze the results. Second, it provides a series of lessons learned, drawn from local cases studies, on how to support the adoption of cost effective solutions. Finally, it gives guidelines on how to include cooking and productive energy access considerations in the tool.

The country-scale analyses presented in the results section of the cover essay along with several subsequent applications of this work show how the tool can be applied to support energy access decision-making in several ways, such as (a) using the model for the fast evaluation of single electrification projects, (b) combining the model with GIS analyses for

producing national-wide electrification analyses, (c) using the tool for capacity building and training purposes, and (d) incorporating it into policy monitoring processes²⁶.

The tool development and applications resulted in a number of valuable research insights.

The tool helps quantify cost trade-offs regarding the target level of electricity access. This thesis stresses the importance of setting energy access goals that are as detailed as possible, and suggests the usage of the Multi-Tier metric developed by the World Bank for that. In fact, different access targets have different costs. Each tier of electricity access increase is potentially several times more costly than the previous one. For instance, achieving the highest electricity access tier could be as much as 100 times more expensive as achieving the lowest. Using such a tool combined with GIS analyses can support the estimations of the costs of a national electricity access policy, and help determine access targets per considered region given constrained budgets.

For the tool application, in parallel to setting detailed energy access goals, tracking energy access progress is crucial for understanding the starting point, and for verifying the effectiveness of electrification policies. Future energy access tracking could be done with the Multi-Tier framework as more data becomes available. However, given the current lack of country data with the Multi-Tier framework, this thesis proposes the usage of the Multi-Dimensional Energy Poverty Index for monitoring energy access. In fact, presenting MEPI results for 54 countries, this thesis provides insights on how energy access evolved over time. One key result for selected countries is that even if the amount of energy poor people do not change significantly over time, the intensity of their energy poverty decreased. This results stresses again the importance of setting detailed energy access goals to really understand the effectiveness of energy policies.

The tool development also gave insights on the key technology tradeoffs to consider when comparing electricity access options. The first technology tradeoff is the one between grid expansions as compared to off-grid solutions. As seen in the results sections low population densities and low energy demand tend to favor off-grid solutions and high densities and high energy demand favor on-grid solutions. The tool, applied to either single locations or at a national scale, support the quantification of this trade-off. Additionally, local resource availability and costs determine the cost competitiveness of electricity-access solutions. The tool permits the comparison of solar, wind, mini-hydro, biogas and diesel powered technologies, and can be easily expanded to include new technologies. Combined with local resources assessment, it can support rural electrification agencies in picking locally-appropriate and cost-effective technologies.

The cost trade-offs present when choosing among cooking solutions are similar to the ones present when considering electricity access solutions. Also for cooking access planning

²⁶ Indeed the monitoring and verification of electrification policies and process can help improve the tool developed. It can provide feedback not only electrification access, but also for re-working the approach to include real-world constraints that have been overlooked in this first iteration.

appropriate metrics will be needed. This thesis proposes the usage of the Multi-Tier framework in combination with the ISO standards for cook stoves for setting cooking access goals. Additionally, the MEPI proves useful in analyzing the current and past cooking energy access status. When choosing among cooking options, stoves characteristics and local resource availability will have to be considered to promote locally cost-effective solutions.

Finally, the inclusion of considerations regarding productive uses of energy access in energy access planning can result in a number of benefits. On one hand, reliable energy access and efficient energy usage are key to maximize productivity. On the other, in certain cases productive activities can facilitate energy access for the local communities.

4.1. Thesis limitations and future research

This thesis aims at supporting quantitative analysis needed by practitioners. They need solutions to understand how to allocate limited funding for energy access-and-use (and the implications thereof). While the work presents valuable new insights regarding important quantitative as well as some qualitative aspects of the energy access challenge, other related issues could not be investigated.

First of all, the work is tailored to support an audience of analysts and policy makers in the specific task of selecting energy access targets and cost-optimal solutions for achieving them. To significantly focus on one part led to overlook some other important aspects of the energy access challenge, such as the analysis of market, behavioral forces and gender concerns amongst others. Technology diffusion aspects were also not considered.

The tool developed in focus 3 could be improved in several ways. For instance, directly relating the electricity demand to the World Bank's Multi-Tier framework, energy efficiency aspects were not considered. Energy efficiency could be an additional option to provide the same services at a lower cost. The possibility of electrical load shifting was not considered. That option could reduce the peak loads, and therefore installation costs. Also, the model could be integrated directly into GIS, thus easing geospatially specific comparisons of energy access solutions. However, while not the focus of this work, GIS analysis may reveal future weaknesses. For example, distance from the grid is treated as a homogenous variable. While distance from the grid by tarred road, is very different to distance from the grid by trail. Yet neither is distinguished in this effort.

4.2. Impact of the thesis work

In line with its objective, this work aspires to having a meaningful impact on informing policy and decision making in energy access. To this end, a number of channels are being (and will be) used.

The first is dissemination. This work was featured in several cutting-edge publications. As seen in section 1.5 of the cover essay it has been included in key energy publications, such as the International Energy Agency's World Energy Outlook, and the flagship publication of

the Sustainable Energy for All Program. Additionally, the standard peer reviewed publications are being generated.

The electrification tool developed in this thesis was used in subsequent work that is not the focus of this thesis, but rather indicates the value of the addition. The tool is used as an engine in GIS work for the United Nation's Modelling Tools for Sustainable Development Policies – Tool for Universal Access to Electricity, where electrification costs and technology considerations for all the 48 Sub-Saharan countries are presented depending on the target levels of energy access [68]. That provides an interactive platform for comparing electrification options on a country-scale depending on local parameters and electricity access targets (measured using the WB's tiers of energy access). Results are presented both in terms of least cost geographical share of stand-alone, mini-grid, and grid-based solutions, and in terms of total costs.

Locally, the work was developed with the support of several governmental organizations and companies dealing with energy access projects. For instance, the work presented in paper II for the Brazilian case study was developed in the field with support from the local energy concessionary (Eletronorte) and the utility (Celpe). Similarly, the Tanzanian work presented in paper 4 was developed with the support of the local utility (TanESCO) experts and other local public organizations (such as The Tanzania Sisal Board). Several companies dealing with the production, transmission and usage of energy in rural areas contributed to the study (such as DD Ruhinda, Renetech and ABB).

Internationally, selected findings of the research work were discussed in a side event at the 2015 Paris Climate Conference (COP21) [69]. Also, applications of the tool were discussed in January 2016 at the seminar 'How GIS is changing the way we do access?' organized by the World Bank group in January 2016. The country case studies results presented in paper V, and in the focus 3 of the thesis, have been reviewed for the IEA by experts from the countries featured in the cases studies of Ethiopia, India and Nigeria amongst others.

Finally, the work presented in the thesis was used to support several capacity building activities. Most notably, in November 2015, 15 analysts from the Ministry of Water, Irrigation & Energy of Ethiopia were trained at the Royal Institute of Technology on how to use the model presented in focus 3 of the thesis for the comparison of electrification solutions.

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Appended papers