Spatially explicit electrification modelling insights

Applications, benefits, limitations and an open tool for geospatial electrification modelling

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Abstract

Developing countries confront the challenge of generating more electricity to meet demands in a sustainable manner. According to the World Bank's 2015 Global Tracking Framework, roughly 15% of world population (or 1.1 billion people) lack access to electricity, and many more rely on poor quality electricity supplies. In September 2015, the United Nations General Assembly adopted Agenda 2030 comprised of a set of 17 Sustainable Development Goals (SDGs) and defined by 169 targets. "Ensuring access to affordable, reliable, sustainable and modern energy for all by 2030" is the seventh goal (SDG7). While energy access refers to more than electricity, it is the central focus of this work.

Models addressing electrification and access typically need large volumes of reliable energy-related data and information, which in most developing countries have been limited or not available. This paucity of information has decelerated energy planning in the developing World. That situation has fundamentally changed with increasing availability and application of Geographic Information Systems (GIS). GIS layers can provide location specific energy-related information that has not been previously accessible. The focus of this thesis lies on integrating a simple electricity supply model into GIS. In so doing a novel open source spatial electrification tool is developed. It estimates power capacity needs and associated investment (and other) costs for achieving universal access to electricity in developing countries.

The dissertation includes a cover essay and six appended papers presenting quantitative methods on coupling selected aspects of GIS and energy systems. It strives to answer three key research questions.

The first research question is: What is the spatially explicit renewable energy potential that can be technically and economically exploited? This information is currently either missing or scattered in developing countries. The provision of low cost, locally available energy can provide a significant opportunity to empower a better standard of living. The first paper presents a GIS based approach to assess the onshore technical wind energy potential on the African continent by applying socioeconomic and geographic restrictions regarding the localization of wind farms and state of the art wind data analysis. The second paper builds on this knowledge and moves one step further by assessing the economic potential and providing cost indicators to assess the viability of wind power (this time in India).

The third paper maps the economic wind power potential in Africa based on the methodologies developed in the two preceding papers. Not only wind power but most energy resources have a spatial nature and their availability is linked to geography. Evaluating these other energy sources (solar, hydro etc.) are included and analysed in Papers IV-VI.

The second research question is: what is the least-cost set of technologies needed to meet different levels of electricity use accounting for different geographies? Increasing access to electricity effectively requires, inter alia, strategies and programmes that address and account for the geographical, infrastructural and socioeconomic characteristics of a country or region. Paper IV introduces a GIS based methodology to inform electrification planning. It builds on the previous work by taking into account the techno-economic wind, and other resource mapping. This methodology is applied in Nigeria in order to determine the least cost technology mix considering the country's infrastructure and resource availability on a spatial basis. Paper V utilizes this method and in so doing demonstrates the importance of geospatial calculations in energy access planning. It highlights differences in investment estimates between alternate scenarios with regards to energy demand and technology deployment. Paper VI enhances this methodology and applies it to every square kilometre of Sub-Saharan Africa. The method is subsequently implemented in an Open Source Spatial Electrification Tool (OnSSET) to facilitate education, repeatability and further research.

Finally, the third question is: Are there gains to be had by linking geographically explicit analysis with typical (non-spatially explicit) long term energy systems models? The work shows that not only do long-term systems models influence geospatially optimal technology deployment. But vice versa, their output influences long term systems models' investment profile. That is because the geospatial disaggregation allows for a better determination of grid versus off-grid connections, and in turn power demand on the national grid. This thesis demonstrates that energy system models should take into consideration the geographic dimension of energy-related parameters, as these play a fundamental role in determining the optimal energy system of a region.

Sammanfattning

Utvecklingsländerna står inför utmaningen att generera mer el för att möta krav på ett hållbart sätt. Enligt Världsbankens Global Tracking Framework 2017 saknar ungefär 15% av världsbefolkningen (eller 1,1 miljarder människor) tillgång till el, och många fler är beroende av elförsörjning av dålig kvalitet. I september 2015 antog Förenta nationernas generalförsamling Agenda 2030 som består av en uppsättning av 17 mål för hållbar utveckling (SDG) och definieras av 169 mål. "Att säkerställa att alla har tillgång till tillförlitlig, hållbar och modern energi till en överkomlig kostnad år 2030" är det sjunde målet (SDG7). Medan energitillgången refererar till mer än el är det det centrala fokuset på detta arbete.

Modeller som gäller elektrifiering och energitillgång behöver vanligtvis stora volymer av tillförlitlig energirelaterad data och information, som i de flesta utvecklingsländer har varit antingen begränsade eller inte tillgängliga. Bristen på information har gjort att energiplaneringen i utvecklingsländer går långsamt. Denna situation har i grunden förändrats med ökande tillgänglighet och tillämpning av Geographic Information Systems (GIS). GIS kartor kan ge platsspecifik energirelaterad information som inte varit tillgänglig tidigare. Fokuset för denna avhandling ligger på att integrera en enkel elförsörjningsmodell i GIS. Därigenom utvecklas ett nytt open source spatial elektrifieringsverktyg. Det uppskattar energi-kapacitetsbehovet och därtill hörande investeringar (och andra kostnader) för att uppnå universell tillgång till el i utvecklingsländer.

Avhandlingen innehåller en uppsats och sex bilagor som presenterar kvantitativa metoder för koppling av utvalda aspekter av GIS och energisystem. Den strävar efter att svara på tre viktiga forskningsfrågor.

Den första frågan är: Vad är den geospatiala förnybara energipotentialen som kan utnyttjas tekniskt och ekonomiskt? Denna information saknas för närvarande eller är utspridd i utvecklingsländer. Tillhandahållandet av lokalt tillgänglig energi till en låg kostnad kan ge en betydande chans att möjliggöra en bättre levnadsstandard. Den första artikeln presenterar ett GIS-baserat tillvägagångssätt för att uppskatta den tekniska potentialen för vindkraft på den afrikanska kontinenten genom att tillämpa socioekonomiska och geografiska restriktioner angående lokalisering av vindkraftparker och toppmoderna vinddataanalyser. Den andra artikeln bygger på denna kunskap och går ett steg längre genom att bedöma den ekonomiska potentialen och ge kostnadsindikatorer för att bedöma

lönsamheten hos vindkraft (den här gången i Indien). Den tredje artikeln kartlägger den ekonomiska vindkraftpotentialen i Afrika baserat på de metoder som utvecklats i de två föregående artiklarna. Inte bara vindkraft men de flesta energiresurser har en spatial natur och deras tillgänglighet är kopplad till geografi. Utvärdering av dessa andra energikällor (sol, vatten etc.) ingår och analyseras i artiklarna IV-VI.

Den andra frågan är: Vilken är den mest kostnadseffektiva tekniken som behövs för att möta olika nivåer av elanvändning med tanke på olika geografiska områden? Ökad tillgång till el kräver bland annat strategier och program som adresserar och redovisar de geografiska, infrastrukturella och socioekonomiska egenskaperna hos ett land eller en region. Artikel IV introducerar en GIS-baserad metod för att informera elektrifieringsplanering. Den bygger på det föregående arbetet genom att ta hänsyn till den techno-ekonomiska vinden och annan resurskartläggning. Denna metod tillämpas i Nigeria för att bestämma den mest kostnadseffektiva teknologi mixen med tanke på landets infrastruktur och resurstillgänglighet på rumslig basis. Artikel V använder metoden och visar därigenom vikten av geospatial beräkningar i planeringen av energiåtkomst. Den framhäver skillnader i investeringsuppskattningar mellan alternativa scenarier med avseende på energibehov och teknikutnyttjande. Artikel VI avancerar den här metoden och tillämpar den på varje kvadratkilometer i Subsahariska Afrika. Metoden implementeras därefter i ett Open Source Spatial Electrification Tool (OnSSET) för att underlätta utbildning, repeterbarhet och ytterligare forskning.

Slutligen är den tredje frågan: Finns det vinster att ha genom att länka geografiskt explicit analys med typiska (icke-rumsligt explicit) långsiktiga energisystemsmodeller? Arbetet visar att inte bara långsiktiga systemmodeller påverkar geo-spatially optimal teknikutplacering. Men vice versa påverkar deras produktion långsiktiga systemmodellers investeringsprofil. Det beror på att geo-rumslig disaggregering möjliggör en bättre bestämning av grid versus off grid förbindelser, och i sin tur kraven på elnätet. Denna avhandling visar att energisystemmodeller bör ta hänsyn till den geografiska dimensionen av energirelaterade parametrar, eftersom dessa spelar en grundläggande roll vid bestämning av det optimala energisystemet i en region.

Acknowledgements

This PhD thesis and the research associated with it took place in a social context and includes several people, whom I would like to thank sincerely and to whom I am greatly indebted. Foremost, I would like to express my sincere gratitude to my supervisor Prof. Mark Howells for the inspirational support during my Ph.D. studies, the invaluable scientific guidance and the innovative thinking. I would also like to express my genuine gratitude to Prof. Holger Rogner who has been the co-supervisor of this thesis and provided insightful comments and encouragement throughout this research work. I could not have imagined having a better advisor and mentor. Further, my work profited significantly from the fruitful collaboration with our affiliate Prof. Morgan Bazilian.

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Last but not least, I would like to thank my family: my wonderful parents Ioulia and Andreas and my -best in the world- brother Christos for supporting me spiritually throughout my studies in Stockholm and for their unconditional love. Most grateful I am to my grandparents Mairi and Mimis, who have been the ones I will always be indebted for their unwavering support and the qualities they imparted to me. Many thanks to Aegli, Nikos and Giannis, who were the driving force that brought me to Sweden, to Takis for his inspirational and educating inputs throughout my studies, my family in Larissa and to Andreas, who despite the distance has always been there. Finally, I would like to thank my beloved Johanna for encouraging me through this experience and for lighting up my life when the lab lights were off.

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1 Introduction

Energy is an essential factor for sustainable development and poverty eradication. It is a critical service highly interconnected with socioeconomic development and well-being. Nevertheless, it is estimated that nowadays still about 3 billion people have no access to modern energy services, while life without electricity is a reality for over 1.1 billion people (1). The vast majority (more than 85%) of these people are located in rural areas in Sub-Saharan Africa, developing Asia, and some parts of central and South America (see Figure 1). These people also rely exclusively on conventional fuels (firewood, kerosene etc.) in order to cover their daily energy needs, which in many cases cause harmful effects to themselves and their environment (2). This calls for a shift towards sustainable forms of energy. This thesis focuses on the most convenient form of energy; i.e. electricity.

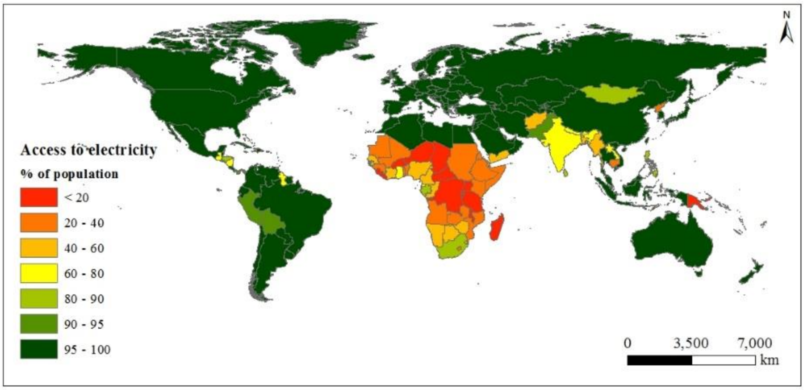

Figure 1: Access to electricity in 2012 (% of population)

Thanks to its adaptable nature, electricity is currently a preferred and convenient form of energy and has become essential for the normal functioning of modern civilization. It can be easily converted into other forms of energy (such as heating, lighting, mechanical energy etc.) (3,4). Electrically operated devices have simple and convenient starting, control and operation and are not associated with smoke and/or poisonous gases. Furthermore, electricity can be easily transmitted from one place to another with the help of conductors (5).

Access to modern, less polluting and affordable electricity is intrinsic to sustainable development. Early electrification is a key enabler for socio-economic development. Studies point out that the very first kilowatt-hours provided, already are beneficial to human development. The level and the quality of health services, education, gender equality, indoor environment, daily activities such as lighting, heating, cooking and transportation as well as business, agricultural, infrastructure and telecommunications sectors can all be upgraded with access to modern energy services (6–8).

Following the brief introduction to the energy access challenge in developing countries, the remainder of this chapter is structured as follows: Section 1.1 provides background information regarding the need for integrating Geographic Information Systems (GIS) and energy system modelling approaches. Sections 1.2 and 1.3 introduce the scope and aim of this dissertation and present the research questions. The overall thesis organization (Section 1.4) and the statement of contribution (Section 1.5) follow.

1.1 Background

The general paucity of reliable energy-related information and georeferenced socio-economic data in developing countries hampers analysis and planning (9–12). However, access to such information and data is vital for assessing, planning, implementing and monitoring the delivery of basic energy services. Electricity access and associated infrastructure planning cannot be addressed without due regard of the spatial nature and dynamics of human settlements and economic production (13). Data requirements increase dramatically for spatial energy analyses compared to traditional energy analyses while data availability can become proportionally sparse.

The use of ground level geospatial data is essential to identify the potential of energy resources as well as the most effective electrification strategy (14). However, such geospatial data have often been either non-existent, fragmented, or inconsistent, which deteriorates their use for strategic planning. GIS tools have been applied for regional spatial analysis in general and even more so when the lack of energy-related data and information would prevent analyses in the first place. Nonetheless, the coupling of GIS and energy system based planning tools is still in its infancy. This thesis aims to address this challenge and better approach the spatial dynamics of energy planning.

1.2 Rationale

Energy system planning is essential in order to match demand and supply, and minimize the associated cost. Moving from centralized electricity generation and transmission and distribution, towards fluctuating, decentralized energy production necessitates considerable alterations of energy infrastructure. Even though local approaches to energy planning are inherently motivated by geospatial questions and challenges, a comprehensive integration of GIS and energy systems planning tools is still missing.

1.3 Aim

The overall aim of this thesis is to link GIS and energy planning by: (1) utilizing recently available open source GIS datasets to estimate techno-economic potential of local energy resources, (2) developing and applying a geospatial electrification toolkit providing least cost mix of technologies for universal access to electricity and (3) introducing the benefits and limitations of GIS in energy planning.

Three research questions form the basis of this thesis. These are the following:

Research question I: What is the spatially explicit renewable energy potential that can be technically and economically exploited?

There has been a significant shortage of information related to energy system characteristics in developing countries. These can include potential of energy sources, actual installed systems and present energy utilization. This lack of knowledge has been apparent for renewable energy sources, which makes the comparison of various energy options difficult. At the same time, the current situation of modern energy and electricity access in developing countries is problematic, where 15% of the world's population reside in areas with no access to electricity. The majority of those without access live in rural areas. This combined with the low ability and willingness to pay (affordability), the low energy consumption per capita, as well as the low electrification rates of rural areas, have traditionally pushed rural communities to make use of locally available energy sources. This is mostly biomass from agriculture residues and forest wood for daily cooking and heating needs.

Fossil fuel energy systems have associated risks related to economic and socio-political instability, insecurity, development and technical failure (15). Further, most developing nations are net importers of fossil fuels (16), a fact that makes them vulnerable to market volatility and affects the national debt of these countries as imported fossil fuels entail significant money flows leaving the country (17). Moreover, fossil fuel technologies, such as diesel generators, are often out of reach for people in remote areas due to high fuel costs.

Adding renewable energy technologies into the generation mix can help alleviate some of these issues. Exploiting a larger share of the local untapped renewable energy potential in developing countries (18,19,11), requires a comprehensive estimation of the energy yield based on the local specificities of a given area.

Research question II: What is the least-cost set of technologies needed to meet different levels of electricity use accounting for different geographies?

Although the importance of energy services for economic and social development has long been recognized (20), energy was not one of the Millennium Development Goals. Its replacement, Agenda 2030 for Sustainable Development - a set of 17 sustainable development goals (SDGs) with 169 associated targets for 2030, lists sustainable energy as a SDG in its own right. SDG7 focuses on a concerted global effort to ensure access to affordable, reliable, sustainable and modern energy for all by 2030 [1] (21). SDG7 targets the elimination of energy poverty which otherwise would remain an incessant threat to the attainment of Agenda 2030 and other SDGs.

Electrification is a priority item for the implementation of SDG7, especially in the least developed countries and regions. The realization of SDG7 is tall order with tough demands on energy infrastructure development, clean energy technology deployment, technology transfer, international cooperation and, above all, finance and sound policy and decision-making. Comprehensive energy infrastructure planning is a necessary first step for the development of viable electrification strategies.

Research question III: Are there gains to be had by linking geographically explicit analysis with typical (non-spatially explicit) long-term energy systems models?

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[1] SDG 7 targets: By 2030, ensure universal access to affordable, reliable and modern energy services, increase substantially the share of renewable energy in the global energy mix and double the global rate of improvement in energy efficiency.

GIS is a system that is designed to capture, store, analyse, handle, manage and visualize different types of spatial or geographic data[2](24). GIS is a broad definition that encompasses a variety of different technologies and methods that allow the user to analyse spatial data information in a range of different fields including engineering, business, public policy and regulations (25).

With previously limited information and data available in developing countries, GIS can help fill some gaps, by utilizing remote sensing data. Decision and policy makers, have recognised the significance of making comprehensive decisions based on information derived from well-designed geospatial databases (26).

Within energy planning, the geography of energy systems plays an important role. Energy end use, energy conversion, energy transport and certain energy sources are geographically distributed. This spatial distribution influences the design of energy systems. Integrating GIS with energy system modelling enables the generation of a more comprehensive picture of energy systems.

1.4 Thesis Organization

This thesis includes reflections of six independent yet interrelated research papers, each one related to a peer reviewed scientific article as shown in the following logical flowchart. All papers deploy Geographic Information Systems (GIS) to answer key issues of energy systems. Each study is performed in order to reach the final objective of this thesis, which is the development of an open source spatial electrification tool and its application in developing countries.

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[2] "Spatial data" refers to information about the locations and shapes of geographic features and the relationships between them, usually stored as coordinates and topology (22). In GIS, spatial is also referred to "based on a location on a map".

"Geographic data" can be defined as a class of spatial data in which the frame is the surface and/or near the surface of the Earth (23).

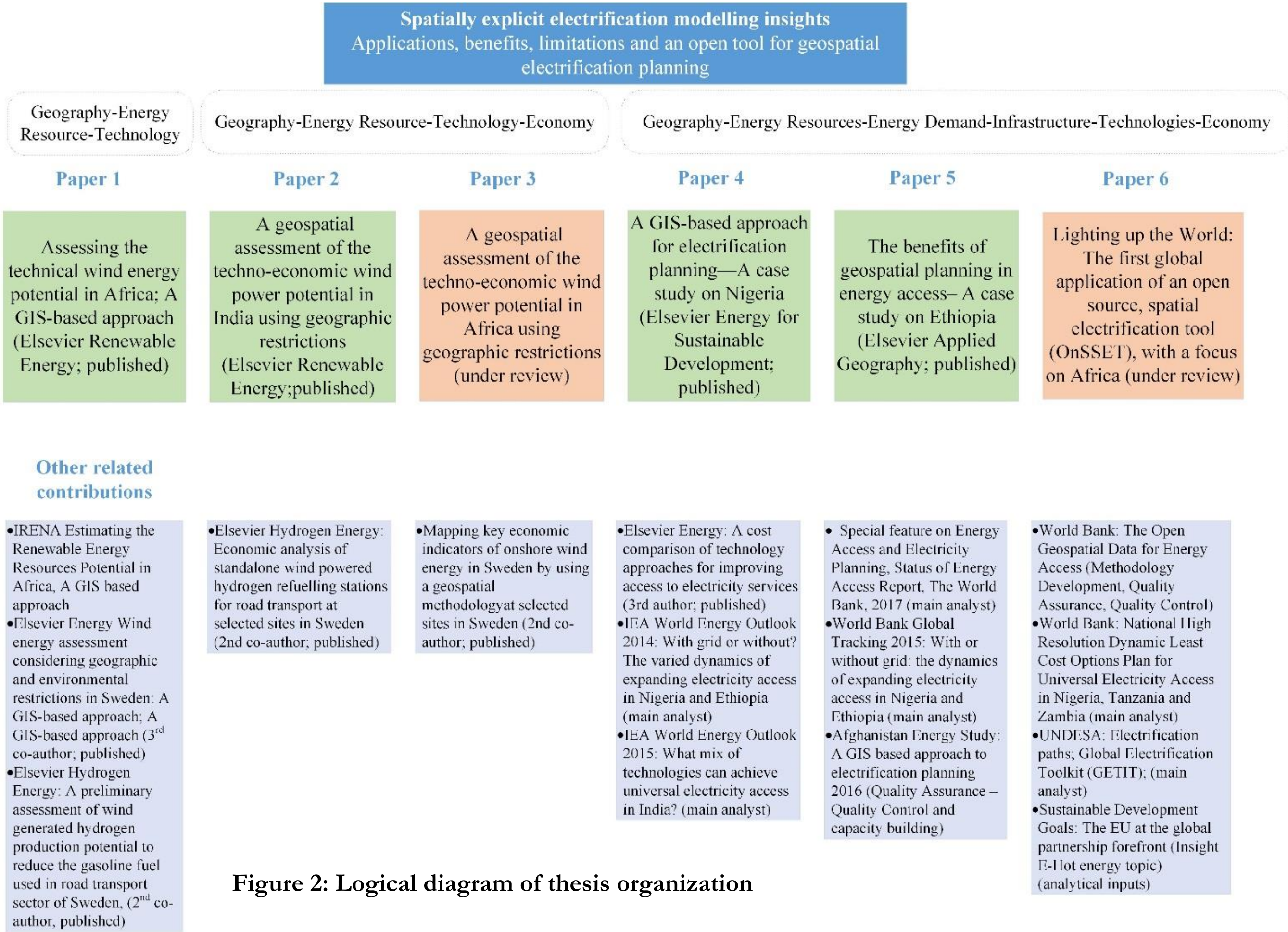


Figure 2: Logical diagram of thesis organization

The first paper presents a GIS based approach to estimate the technical wind energy potential on the African continent. It accounts for socioeconomic and geographic restrictions regarding the localization of wind farms and state of the art wind data analysis and uses publicly available datasets. This constitutes an essential input for the spatial electrification analysis.

The second paper builds on this knowledge and moves one step further by assessing the economic potential and providing a cost indicator to assess the viability of wind power. The analysis focuses on India. Economic potential is given as Levelized cost of generating electricity; an output that can be used for comparing the costs of generating electricity from different energy sources.

The third paper presents a case study on the techno-economic wind power potential on the African continent based on the methodologies developed in the first two papers. It advances the costing methodology by considering the topological characteristics of the studied areas.

The fourth paper not only assesses the potential of these resources but also compares the cost of a matrix of mature electrification technologies taking into account demand related parameters, such as spatial population density, distance to transmission network, other energy sources that have spatial nature, mining sites, power generation infrastructure and others. The result is a least cost electrification solution for all settlements in Nigeria. A geospatial electrification model is introduced, which forms the basis of the open source spatial electrification toolkit (OnSSET).

In parallel, *the fifth paper* utilizes the developed geospatial electrification model to assess the importance of geospatial planning in energy access, using the case study of Ethiopia. It highlights differences in needed investments between alternate scenarios with regards to energy demand and technology deployment which would not be apparent without a spatial analysis.

The *sixth paper* introduces an enhancement of the geospatial electrification model. It is applied to all unelectrified countries in Africa. It uses open source datasets (and software) to provide an investment outlook for universal access for 10 different scenarios (5 electricity demand levels and 2 oil prices). It introduces also a market assistance need index to highlight where international assistance for development is most needed.

A list of the papers follows:

Paper I

Mentis, D., Hermann, S., Howells, M., Welsch, M., Siyal, S.H., 2015. Assessing the technical wind energy potential in Africa: a GIS-based approach. Elsevier Renewable Energy 83, 110–125.

Paper II

Mentis, D., Siyal, S.H., Korkovelos, A., Howells, M., 2016. A geospatial assessment of the techno-economic wind power potential in India using geographic restrictions. Elsevier Renewable Energy 97, 77–88.

Paper III

Mentis, D., Siyal, S.H., Korkovelos, A., Howells, M., under review. A GIS based study to estimate the spatially explicit wind generated electricity cost in Africa. Elsevier Energy Strategy Reviews.

Paper IV

Mentis, D., Welsch, M., Fuso Nerini, F., Broad, O., Howells, M., Bazilian, M., Rogner, H., 2015. A GIS-based approach for electrification planning—A case study on Nigeria. Elsevier Energy for Sustainable Development 29, 142–150.

Paper V

Mentis, D., Andersson, M., Howells, M., Rogner, H., Siyal, S., Broad, O., Korkovelos, A., Bazilian, M., 2016. The benefits of geospatial planning in energy access – A case study on Ethiopia. Elsevier Applied Geography 72, 1–13.

Paper VI

Mentis, D., Howells, M., Rogner, H., Korkovelos, A., Arderne, C., Zepeda, E., Siyal, S.H., Taliotis, C., Bazilian, M., De Roo, A., Tanvez, Y., Oudalov, A., Scholtz, E., under review. Lighting the World, The first global application of an open source, spatial electrification tool (OnSSET), with a focus on Sub-Saharan Africa. Environmental Research Letters Special Focus on Energy Access for Sustainable Development.

The relation between appended papers and research questions is illustrated in Table 1.

Table 1: Relation between appended papers and research focuses in the thesis

Note: Dark grey and light grey shaded cells represent papers that provided significant and moderate contributions respectively to the research focus of the thesis

Research questions	**Paper**					
	I	**II**	**III**	**IV**	**V**	**VI**
I. What is the spatially explicit renewable energy potential that can be technically and economically exploited?						
II. What is the least-cost set of technologies needed to meet different levels of electricity use accounting for different geographies?						
III. Are there gains to be had by linking geographically explicit analysis with typical (non-spatially explicit) long-term energy systems models?						

Additionally, the following publications and author's contributions to reports and books' chapters served to inform this thesis. Although these publications are referenced in sections of the cover essay and the appended papers, they do not represent an integral part of this thesis.

I. Howells, M., Rogner, H., **Mentis, D.,** Broad, O., Special feature on Energy Access and Electricity Planning, Status of Energy Access Report, The World Bank, 2017

II. **The World Bank,** A GIS approach to electrification planning in Afghanistan, 2017

III. Moksnes N., Korkovelos A., **Mentis, D.**, Howells, M., under review in Environmental Research Letters. Electrification pathways for Kenya – linking spatial electrification analysis and medium to long term energy planning

IV. Sahlberg, A., Khavari, D., Korkovelos, A., **Mentis, D.**, Howells, M., under review in Environmental Research Letters. A GIS approach to electrification planning in Zambia. The first application of the online interface of the Open Source Spatial Electrification Tool (OnSSET)

V. Korkovelos A., **Mentis D.**, Siyal, S.H., Arderne, C., Rogner, H., Bazilian, M., Howells, M., Beck, H., De Roo, A., under review in Elsevier Applied Geography. A geospatial assessment of small-scale hydropower potential in Sub-Saharan Africa

VI. Fuso Nerini, F., Broad, O., **Mentis, D**., Welsch, M., Bazilian, M, Howells, M., 2016. A cost comparison of technology approaches for improving access to electricity services. Elsevier Energy. 95, 255-265

VII. **International Energy Agency**, World Energy Outlook 2015. Selected contributions to the India Chapter, Focus on electricity access in India, 2015

VIII. **International Energy Agency**, World Energy Outlook 2014. Selected contributions to the Africa Chapter, Focus on electricity access in Nigeria and Ethiopia, 2014

IX. **International Energy Agency and the World Bank,** Sustainable Energy for All 2015-Progress Toward Sustainable Energy, World Bank, Washington, DC. Selected contributions to the energy access and nexus chapters, 2015

X. Siyal, S.H., **Mentis, D.,** Howells, M., 2016. Mapping key economic indicators of onshore wind energy in Sweden by using a geospatial methodology. Energy Convers. Manag. 128, 211–226.

XI. Siyal, S.H., **Mentis, D**., Mörtberg, U., Samo, S.R., Howells, M., 2015a. A preliminary assessment of wind generated hydrogen production potential to reduce the gasoline fuel used in road transport sector of Sweden. Int. J. Hydrog. Energy 40, 6501–6511.

XII. Siyal, S.H., Mörtberg, U., **Mentis, D.,** Welsch, M., Babelon, I., Howells, M., 2015b. Wind energy assessment considering geographic and environmental restrictions in Sweden: A GIS-based approach. Energy 83, 447–461.

XIII. Siyal, S.H., **Mentis, D.**, Howells, M., 2015a. Economic analysis of standalone wind-powered hydrogen refueling stations for road transport at selected sites in Sweden. Elsevier International Journal of Hydrogen Energy.

XIV. Welsch, M., **Mentis, D.**, Howells, M., 2014. Chapter 17 - Long-Term Energy Systems Planning: Accounting for Short-Term Variability and Flexibility A2 - Jones, Lawrence E., in: Renewable Energy Integration. Academic Press, Boston, pp. 215–225.

XV. **Mentis, D.**, Karalis, G., Zervos, A., Howells, M., Taliotis, C., Bazilian, M., Rogner, H., 2016. Desalination using renewable energy sources on the arid islands of South Aegean Sea. Elsevier Energy 94, 262–272.

XVI. **United Nations Economic Commission of Europe**: Reconciling resource uses in transboundary basins: assessment of the water-food-energy-ecosystems nexus, 2015 (Analytical inputs)

XVII. **United Nations Economic Commission of Europe**: Reconciling resource uses in transboundary basins: assessment of the water-food-energy-ecosystems nexus in the Syr Darya River Basin, 2017 (Analytical inputs)

XVIII. **Mentis, D.**, 2014. Electrifying Greece with solar and wind energy. Journal of Thermal Science. 18, 709–720.

XIX. Sridharan, V., Howells, M., Gabrielle, D., Hafner, M., Mistré, M., **Mentis, D.,** 2016. Hot Energy Topic: Sustainable Development Goals: The EU at the global partnership forefront

XX. Taliotis, C., Shivakumar, A., Ramos, E., Howells, M., **Mentis, D.**, Sridharan, V., Broad, O., Mofor, L., 2016. An indicative analysis of investment opportunities in the African electricity supply sector — Using TEMBA (The Electricity Model Base for Africa). Elsevier Energy for Sustainable Development 31, 50–66.

1.5 Statement of Contribution

All analyses, methodologies and substantial write up of Paper I-Paper VI were developed and performed by the main author under the supervision of Professor Mark Howells and Professor Holger Rogner. Other co-authors have contributed with data collection and significant insights that improved the intellectual context of the papers.

Paper I

All analyses, methodologies and substantial write up of Paper I were developed and performed by the main author under the supervision of Professor Mark Howells. Sebastian Hermann, the 2nd author proposed the topic of this paper aiming to contribute to IRENA's report on Estimating the Renewable Energy Potential in Africa: A GIS-based approach. Other co-authors (Manuel Welsch, Shahid Siyal and Mark Howells) contributed with insights that improved the intellectual context of the paper.

Paper II

All analyses, methodologies and substantial write up of this paper were developed and performed by the main author under the supervision of Professor Mark Howells. Other co-authors (Shahid Siyal, Alexandros Korkovelos) contributed with insights that improved the intellectual context of the paper.

Paper III

All analyses, methodologies and substantial write up of this paper were developed and performed by the main author under the supervision of

Professor Mark Howells. Other co-authors (Shahid Siyal, Alexandros Korkovelos) contributed with insights that improved the intellectual context of the paper.

Paper IV

All analyses, methodologies and substantial write up of this paper were developed and performed by the main author under the supervision of Professor Mark Howells and Professor Holger Rogner. Manuel Welsch and Oliver Broad contributed in developing the electrification algorithm and Francesco Nerini in data collection. Other co-authors provided insights that improved the intellectual context of the paper.

Paper V

All analyses, methodologies and substantial write up of this paper were developed and performed by the main author under the supervision of Professor Mark Howells and Professor Holger Rogner. Associate Professor Magnus Andersson, the 2nd author of the paper contributed in the spatial distribution analysis of the electrification mix. Other co-authors (Shahid Siyal, Oliver Broad, Alexandros Korkovelos and Morgan Bazilian) provided insights that improved the intellectual context of the paper.

Paper VI

All analyses, methodologies and substantial write up of this paper were developed and performed by the main author under the supervision of Professor Mark Howells and Professor Holger Rogner. Alexandros Korkovelos contributed in the assessment of the mini and small hydropower potential and data collection, Christopher Arderne with the transfer of the electrification algorithm from Visual Basic to Python, and Constantinos Taliotis with the estimations of the country specific cost of generating electricity. Other co-authors (Shahid Siyal, Eduardo Zepeda, Yann Tanvez, Ad de Roo, Alexander Oudalov and Morgan Bazilian) provided insights that improved the intellectual context of the paper.

2 State of the Art

In recent times (26) energy use in developing countries is growing rapidly, which affects security of energy supply, economic recession, climate change as well as regional and global energy systems. Energy models are used to assess future energy system configurations and paths and analyse the effects of energy utilization on the human and natural environment (28). These models serve as test-beds to assess system designs which would be unreasonable, too costly or impossible to test in “real world” conditions (29). This section discusses briefly previous research efforts and projects in the field of energy system modelling and planning with a focus on both non-GIS based models and GIS-based approaches.

2.1 Energy system models

Energy models were first introduced in the 1970s as a result of the oil crisis, the increasing environmental awareness and the rising computer availability (30–32). Energy system modelling is a common method for investigating the optimal operational strategy for generating heat and electricity (33). A plethora of methods and models have been developed over the last decades to analyze the distribution of energy in a time-dependent manner in order to inform the design of energy strategies, aiming to address various questions related to policy, investments and operational aspects (34).

Energy system models can be grouped in different categories depending on their scope (entire energy system or power system, long-term investment decisions or short-term dispatch, supply and/or demand side) and can be also grouped in aggregated top-down macroeconomic or disaggregated bottom-up engineering models (29).

Top-down models provide insights on broad relationships between economic development and the associated energy demand and supply. These models include econometric, input-output and computable general equilibrium approaches. They are typically 1) driven by projected developments of major economic indicators, such as Gross Domestic Product, GDP, population or energy prices (econometric), 2) considering the interdependencies within an economy by capturing the monetary or commodity flows between different branches (input-output) and 3) ensuring that an economy wide general equilibrium between sectoral demands and supplies is satisfied (computable general equilibrium). Top-down models usually do not include details on technology (35).

On the other hand, bottom-up models are largely technology driven and are valuable for investigating issues such as energy-related policies or the role individual technologies could play in the energy matrix of a region (36). Bottom-up models can be grouped further in three categories; accounting frameworks, simulation and optimization models (37). The first ones are driven by exogenous assumptions regarding the interrelations within the energy system and calculate physical flows of energy carriers within the system. Simulation models simulate the energy system under a set of specified conditions related to behavior, operation and investment. Optimization models identify optimal pathways for meeting demand; optimal can be least cost, highest level of energy security, or fastest access to energy services (38,39). The latter have been proven highly useful for planning energy systems on national and international level. As opposed to top-down models, bottom-up fail to take into account cross-sectoral interdependencies (40) and are used to compute partial economic equilibria in the energy sector under different constraints (35).

Hybrid models incorporate aspects of both bottom-up and top-down approaches and are either integrated or soft linked, i.e. transferring data between stand-alone tools in an iterative process. These models help particularly in understanding the impact energy-related greenhouse gas (GHG) emissions, water and land use changes have on climate change (and vice versa) (36,41).

Traditionally, energy system models require a plethora of input data and parameters in order to solve optimization problems in a quasi-useful way (42). In order to keep models solvable in reasonable time and to reduce calibration and other input data requirements, most conventional energy system models consider spatially aggregated regions and a small set of seasonal and daily time slices (43,44). However, the spatial and temporal resolution is important (45).

There are several data related to energy consumption, distribution and generation technologies, which comprise spatial and temporal attributes and need to be considered in order to calculate system costs and conclude to optimal set of technologies. These include information related to intermittent energy resources such as wind, solar, hydro, as well as diesel supply, demand nodes and economic activities. To illustrate, wind power is determined by wind speed and air density, solar power depends on solar irradiance, hydropower on precipitation patterns and topologies, diesel on pump price and proximity to the pump. In addition, the power infrastructure differs from one location to another and so does the demand.

On energy planning, there are some models focusing in different scales; namely rural or regional electrification. The former include HOMER - a micro-optimization software-, RETScreen - a model examining the feasibility of energy efficiency, renewable energy and cogeneration projects (46)-, a rural electrification model developed in TIMES (47) and others. However, these models are typically 'heavy' and require much calibration. One simple, transparent cost model is developed for rural electrification by (48). This calculates the levelized cost of generating electricity for several electrification technologies based on four key parameters, namely: (i) electricity demand target level and quality of energy access, (ii) population density, (iii) local grid connection characteristics and (iv) local energy resources availability and technology cost. Its structure allows for an integration with GIS based models. This integration forms the basis of the Open Source Spatial Electrification Tool (OnSSET).

Furthermore, there are several models available in the literature that provide estimates about the investment requirements to reach universal access to electricity in regional level. A recent study introduced by (16) uses the Access Investment Model (AIM), a model developed to provide greater clarity on the scale of the access challenge based on the multi-tier access framework for electricity. This study estimates approximately 45 billion USD of annual investments to reach full access globally, while 17 billion USD/annum would be needed to provide electricity to all in Sub-Saharan Africa by 2030 [3]. The suggested delivery method would be the following: 100% of the urban population connected to the grid, while just 40% of rural population would connect to the grid, 20% to mini grid systems, 25% to solar lighting systems and about 15% would gain access via rural household systems. Other recent studies also provide estimates for global access to electricity; these are in the range of 12-279 billion USD/year (49), 65-86 billion USD/year (50), 15 billion USD/year (51). However, these estimates are not based on a detailed geographic analysis that considers the population distribution, the resource availability and the power infrastructure across a country.

The simplifications employed by conventional energy system models (e.g. spatially aggregated regions) call for more integrated and granular solutions. This will help incorporating the abovementioned spatio-temporal

[3] This analysis however assumes certain levels of electricity consumption; average urban consumption of 500 kWh/household-year in year 1; average rural consumption of 250 kWh/household-year in year 1; consumption increases to 750kWh/hh-year within first 20 years for all households.

dynamics into energy system models and enable effective power infrastructure planning while considering a growing mix of energy technologies.

2.2 Spatial attributes of energy systems

Geospatial analysis is an effective tool for supporting the planning, implementation and monitoring of basic services delivery in developing countries (52). However, the use of GIS data and associated analytical tools to conduct strategic energy planning remains at an early stage. Yet it has multiplied in recent years to support public and private sectors stakeholders in prioritizing and rationalizing decision making related to energy infrastructure.

2.2.1 GIS and Renewable Energy

There are numerous examples in the literature where GIS have been used as a planning tool for renewable energy infrastructure. More specifically the identification of suitable locations and the mapping of renewable energy resources have been widely studied spanning from local (34,53–59) to national (60–67) and regional assessments (68,10,69–71).

Most of these studies focus on renewable energy supply without considering the location dependent energy demand and the associated costs of delivering energy services.

2.2.2 GIS and Energy Planning

Generally, planning energy distribution systems is essentially reduced to the choice between centralized and decentralized systems. The former focus on a structure exploiting economies of scale at large generation and transmission and distribution infrastructure (72). Yet, there have been several key drivers in the transition towards decentralized and deregulated systems (73). Such include the rising understanding of environmental issues, the advancement of information and communication technologies, and the introduction of new distributed solutions.

Within a context where energy services are increasingly delivered in a decentralized manner and through non-state actors, energy planners and researchers gradually use GIS analysis in order to define national or subnational electrification plans and subsequent strategies and policies. Tiba et al (2010) developed a GIS-based decision support tool for renewable energy planning in rural areas. The tool allows planning of a sizeable addition of renewable energy technologies and the management of the already installed systems. Diverse criteria are considered in order to identify the most favourable location for installing new energy systems. These criteria include solar and wind availability, proximity to transmission network, rural electrification index, income per capita and others. This study though considers mainly the implementation of solar and wind power technologies, overlooking the potential penetration of other technologies (for instance grid expansion or mini hydropower) to provide electricity to unserved areas.

In this direction, Amador et al. (74) highlight a major problem of rural electrification, which is the selection of the most suitable technology. In that study GIS is used to categorize zones into areas that are more appropriate for either conventional or renewable technologies based on techno-economic criteria. The authors use the levelized cost of generating electricity, LCOE, as the metric of choice. In this analysis four parameters are considered and related to costs: rural population density (inhabitants/km^2), annual solar irradiation, annual average wind speed (m/s) and distance of connection to the MV grid (km). This tool has been applied in the municipality of Lorca in Murcia, Spain and verified with coherent results. However, the limited use of GIS data (including the electrical network map, housing map, wind and solar resource maps) and the lack of a grid expansion costing algorithm constitute some key weaknesses of this effort.

A noteworthy study that investigates energy solutions in rural Africa is introduced by (75). A spatial electricity cost model is designed to indicate whether diesel generators, photovoltaic systems or grid extension are the least-cost options in off-grid areas. This analysis points out where grid extensions constitute the cost optimal option based on a set of boundaries that delineate the distance where a potential extension would be feasible, i.e., 10, 30 and 50 km distance from low (LV), medium (MV) and high voltage (HV) lines respectively. These boundaries are however not result of an optimization exercise and should be further examined.

Another substantial effort is undertaken by Kaijuka (2007b) who uses a GIS approach for demand driven rural electrification planning in Uganda, allocating an energy benefit point system to priority sectors (education and health) based on local conditions and available resources in each area. However, this study does not suggest an optimal way to provide electricity to the identified priority areas. (77) introduce a framework that combines mobile phone data analysis, socioeconomic and geospatial data and state-of-the art energy infrastructure engineering techniques to assess the feasibility of a limited number of different electrification options (three) for rural areas, such as extensions of the medium voltage (MV) grid, diesel engine-based micro grids and stand-alone solar photovoltaic (PV) systems.

Similarly, the Network Planner approach (78) considers demand centres and compares the implications of either extending the national grid or rolling out solar PV household systems backed up by diesel generators for productive uses or opting for low voltage diesel based mini-grid systems. The model has been applied to Liberia, Ghana (79) and Nigeria (80). Nonetheless, this tool accounts for a limited number of electrification technologies, considers a limited number of demand nodes and accounts for a static representation of the bulk electricity generation mix.

In the same way, (81) developed the Reference Electrification Model (REM), which extracts information from several GIS datasets in order to determine where extending the grid is the most cost-effective option and where other off grid systems, such as micro grids or stand-alone solar systems, would be more economical. However, the technical potential of renewable energy resources is not scrutinized and the resolution of the analysis is limited to broad administrative areas.

Other geospatial applications (not published in the academic literature) are available in open web platforms. The International Finance Corporation (IFC) has developed an off-grid market opportunity tool (82). This tool uses geospatial information (such as population density, proximity to transmission and road network and others) to help private companies, governments, academia and civil society to develop a high-level view of where markets for off-grid electrification may exist to better inform decision-making. Similarly, the Energy Commission of Ghana developed an energy access toolkit for monitoring and evaluating energy access and renewable energy resources in the country using geospatial datasets (83). However, no electrification analysis is included in these applications in order to identify the cost optimal electrification technology.

The aforementioned sources as well as other recent relevant studies (see Table 2) (84), (85), (86), (87) form the basis for the development of a comprehensive methodology used to fulfil the objectives of this dissertation and address some of the identified weakness of the preceding approaches. To summarise, the majority of the previously developed GIS methods have one or more of the following limitations: they focus on how rural areas should be electrified; they do not provide an overall electrification expansion indication for an entire country; they deploy a limited number of electrification technologies; they use a limited number of GIS data (some of which are proprietary) and with that limit analysis; they use a limited number of demand nodes; they lack a grid expansion costing algorithm or they do not account for a dynamic change of the bulk grid electricity supply mix.

Table 2: Selection of recent GIS electrification studies

Source	Geographical Scope	Level of Resolution	Technologies	Background layers	Open source code/Free software
(74)	Lorca in Murcia, Spain	Municipality level	Grid, off grid solar PV and wind turbine	Housing map, transmission network, wind and solar resource maps	No/No
(76)	Rural Uganda	Sub counties	Off grid solar PV and hydro power	Priority sectors (education and health) and available resources	No/No
(88)	North East Brazil	Municipality level	Off grid solar PV and wind turbine	Solar and wind resource maps, transmission network	No/No
(78)	Liberia	Local Government Areas	Grid versus off grid solar PV and diesel generator	Settlements and other demand points, transmission grid	No/Yes
(89)	Africa	5 km	RET and grid	Population density, solar resource map, travel time, transmission grid	No/No
(79)	Ghana	Local Government Areas	Grid versus off grid solar PV and diesel generator	Settlements and other demand points, transmission grid	No/Yes
(77)	Senegal	Cities, towns, villages	Grid versus off grid solar PV and diesel	Mobile Phone Data, transmission network	No/No

(80)	Nigeria	Local Government Areas	Grid versus off grid solar PV and diesel	Settlements and other demand points, transmission grid	No/Yes
(84)	Kenya	5 km	Grid versus off grid solar PV	Solar availability, transmission network, population density	No/No
(81)	Vaishali District, in Bihar, India	Broad administrative areas	Grid versus off grid solar PV and diesel generator	Solar availability, transmission network, population density	No/No
(90)	Africa	small towns of 30000-50000 inhabitants	Low hanging fruits - Dams and Solar PV	Population density, solar resource map, existing dams, biomass density travel time, transmission grid, night-time light	No/No
(91)	Ghana	Settlements – 1086 Thiesen polygons	Grid versus off grid solar PV, wind turbine and diesel generator	Solar resource map, transmission network, population density	No/No

This thesis varies from the existing studies in a number of ways. It develops a techno-economic tool capable of integrating the spatial dimension of energy resources, energy demand and power network, as well as cost related indicators. There are several significant parameters taken into account that have not been considered thoroughly in the previously stated studies. Such are the techno-economic potential of renewable energy sources, the development of an open source code, grid expansion to cover main economic activities, location of existing and planned power infrastructure, the intensity of night-time lights and others that are mentioned throughout the thesis and the appended papers (see Section 4).

3 Study areas

The importance of GIS in renewable energy resource assessments, energy access and energy planning was studied at two different spatial scales; national and continental and in four different developing regions (continental Africa, India, Nigeria and Ethiopia). In all studies, the highest resolution of relevant publicly available GIS data was used (at the time of writing).

3.1 Africa- renewable resource assessment and electrification planning

Africa is selected as it is the continent with the lowest electrification rate. About 65% of the population (more than half billion people) in Sub-Saharan Africa lack access to electricity (92). There is a significant potential for the African countries to face the challenge of generating more renewable power. According to (93), the continent is endowed with vast renewable energy resources. These are indigenous and therefore enhance countries' energy self-sufficiency by limiting their dependence on imported fossil fuels. Energy self-sufficiency reduces a country's exposure to the price and supply volatility of imported energy, and mitigates the potential negative economic impact. Effective energy planning and thorough resource assessments should be carried out in order to avoid technology lock in and potentially leapfrog investments. By doing so, Africa may avoid some of the negative characteristics inherent in conventional systems and elude some of the same evolutionary steps taken by Europe and North America.

3.2 India- renewable resource assessment

In India, most of the electricity is generated by conventional energy sources, i.e. coal, gas and other fossil fuels; the combustion of which generates significant greenhouse gas (GHG) emissions and exacerbates climate change (94). The total population of India amounts to approximately 1.3 billion, whilst around 240 million people (19% of the country's population) reside in areas that lack access to electricity (2). Moreover, the country relies heavily on imported fossil fuels for power generation (ca 32% fossil fuel import dependence in 2014) (95). The latter might cause energy crises due to unpredicted geopolitical circumstances and potentially deteriorate economic development (96). This calls for a thorough assessment of the local renewable resources to estimate the extent that these would penetrate to the national electricity system and stimulate domestic production.

3.3 Nigeria – electrification planning

Nigeria is Africa's most populous country and the one with the highest deficit in access to electricity (97). Nigeria is also characterized by great energy resource potential (98). It is the largest oil producer and prime holder of natural gas proven reserves in Africa, while the wind and solar power potential are significant (100). However, the country is struggling to supply its citizens with electricity. Nigeria has one of the lowest rates of electricity consumption per capita worldwide (about 149 kWh) and electricity generation falls short of demand resulting in load shedding, black outs and a reliance on private generators. To illustrate, only 45% of the country's population has access to electricity (76 million out of 169 in 2012), while this figure drops to 35% in rural areas (101).

3.4 Ethiopia – electrification planning

Ethiopia is chosen as a case study for spatial electrification planning as the country's per capita electricity consumption is among the lowest globally. Ethiopia's current per capita use amounts to 52 kWh – dismal compared to neighbouring Egypt (1743 kWh/cap) or the USA (13,246kWh/cap) (16). Increasing cost effective and affordable access to electricity and the services it provides is essential for meeting SDG 7. Also, the local renewable energy potential is significant in size. The renewable energy potential in the country is noteworthy (102,103). Despite the local energy resource potential, just over 26% of the country's population has access to electricity (24 million out of 92 million in 2012). In rural areas this figure drops to 10% (101).

4 Methods

The various methods used in this dissertation are presented in this chapter. This section is complementary to the methodologies presented in the six appended papers. Some of the methods that were used multiple times throughout the papers are only described once. The following methodological flowchart displays a simplified overview of all major analytical steps. To start with, this thesis focuses on the use of the most updated publicly available spatial data in order to obtain resource information in the best possible resolution. Moving from resource availability to land availability: the geography and the topology of a studied area are essential in order to estimate the total amount of land area which is available for renewable energy projects. This area is referred to as Geographic Potential. Thereafter available technologies, and associated technical parameters including energy losses and the process of generating electricity are considered in order to estimate the technical potential yield. Restricting further the resource availability, the economic potential is estimated, i.e. the share of the technical potential that can be realized in a cost effective manner given the cost of other energy sources. Finally, several technologies are taken into account, as well as data related to demand side and infrastructure in order to identify the cost optimal electrification mix to provide access to electricity to unserved areas. Detailed flowcharts are presented in the appended papers.

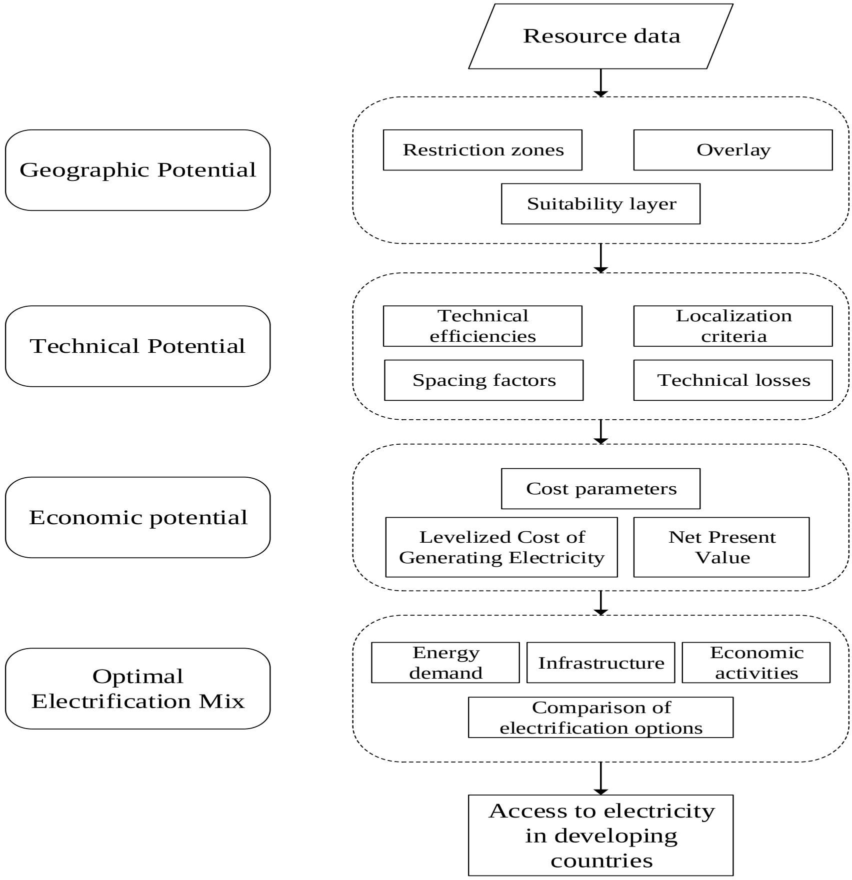


Figure 3: Methodology flowchart

4.1 Spatial techno-economic potential of renewable energy resources

This dissertation focuses initially on developing and applying methods for estimating the technical and economic potential of wind energy in developing countries, where the collection of energy-related data constitutes a major challenge. Methods for other renewable energy technologies are also developed using the most recent publicly available datasets. However, these methods are awaiting publication in peer-reviewed journals and are not in the scope of this dissertation.

Paper I introduces a methodology to assess the technical onshore wind energy potential in Africa after applying geographic restrictions related to the localization of wind farms. The most critical input in wind energy assessment is the wind speed magnitude. Open source raw wind speed data are obtained by the National Aeronautics and Space Administration (NASA). NASA supplies global daily wind speed data at 10 m above ground level at a relatively coarse grid cell resolution of 1^{o} x 1^{o} (122). Using the power law extrapolation formula, wind speed data are scaled up in order to obtain the corresponding values at the hub height (80m) of a selected wind turbine model (here Vestas V90).

The data from NASA are complemented with data from IRENA and Vortex (102). The latter are provided at 80 m and at a much higher spatial resolution (0.067^{o} x 0.067^{o}). However, these data consist of annual mean wind speeds. A finer distribution is attained by combining the wind speed distribution obtained from the daily data (coarser spatial resolution) and the annual mean wind speed (higher spatial resolution) using the bilinear interpolation technique.

The onshore area is restricted to areas that are suitable for wind turbine installations. Water bodies, protected and forest areas, high elevation and sloped areas, urban built-up and agricultural areas as well as areas far from the transmission grid are excluded for the overall wind energy yield estimation. The abovementioned restriction maps are harmonized using GIS resample techniques to bring all datasets in the same format and reclassified in such a way that they show the suitable and not suitable areas for wind farms.

The restricted areas in each criterion are given value "0" while the rest "1". To illustrate, all cells that contain water bodies are given the value "0", while the rest would be available for setting up a wind farm, i.e. value "1" would be assigned to those cells. Similarly, all GIS restriction layers are first reclassified to two binary values. An overlay function is then applied in GIS environment to combine these exclusions to an overall suitability map that provides the geographic wind power potential expressed in km^2.

After determining the available areas for wind farms, the estimation of the wind energy yield follows. The adjusted wind speed distribution is now combined with the power curve of the selected turbine to determine the potential energy yield that could be generated by a wind turbine (see Equation 1). Thereafter other technical parameters are considered before reaching the total technical wind energy potential. Such parameters include: spacing of the turbines, wind farm availability factor, array efficiency, slope factor, mechanical and electrical losses. Detailed equations and methods are included in the appended papers.

Equation 1

$$E_{expected} = \mu \cdot T \int_{U=0}^{U=cut_{out}} P(U) \cdot f(U) dU \approx \mu \cdot T \sum_{wind\ class} P(U) \cdot f(U)$$

Where, $E_{expected}$ is yearly expected wind energy, μ is the availability factor of the wind farm; P(U) is the power curve of selected wind turbine, f(U) is the probability distribution of a wind class. The wind classes considered range from 0 to 25 m/s and each class range is 0.5 m/s., and T is the time in hours of a full year, i.e. 365.25 x 24 hours. Ultimately, the technical wind power potential is estimated for all suitable areas in 46 African countries and expressed in MWh/annum/km^2.

Similarly, Paper II utilizes publicly available wind speed datasets and other socio-economic parameters and geographic layers to come up with the wind power potential in India. Land suitability and the technical potential are not always linked to the feasibility of a renewable energy project. It is therefore essential to introduce economic indicators to assess whether a considered RET is cost competitive to other sources. The levelized cost of generating electricity (LCOE) is an indicator that can be easily communicated to and comprehended by policy makers and energy planners. It represents the final cost of electricity generated by a power plant over its life time and takes into account the investment cost of a power plant, the operating and maintenance costs, the fuel expenditures, the electricity generated and the discount rate (123). Another economic indicator that plays important role in decision making of the wind energy projects is the accumulated Net Present Value of all costs (NPV) (124,125). This is used to estimate the overall costs of a project and can provide insights regarding the viability of a project for both governments and potential investors. These two indicators are enumerated throughout the available areas for wind installations in India (see Equation 2 and Equation 3).

Equation 2

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + O\&M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

where, n is the lifetime of the wind power system (in years)
I_t is the investment cost for a power plant in year (t) (in USD)
$O\&M_t$ are the operation and maintenance costs (in USD/kWh) in year (t)
F_t is the fuel expenditures (in USD/kWh) in year (t)
E_t is the electricity generated (in kWh) in year (t)

r is the discount rate (in %).

Equation 3

$$Accumulated\ NPV\ of\ costs = I_0 + O\&M \left[\frac{(1+r)^n - 1}{r(1+r)^n}\right]$$

where I_0 the initial investment cost (in USD/kW).

Paper III applies the methodologies developed in Papers I-II on the continental Africa. As opposed to the previous papers, it accounts for a topology factor in order to consider for an additional investment cost depending on the topological characteristics of each location (See Equation 4). In this analysis, the existence and the quality of the road network and the land cover types are considered. Also, two different wind turbine models are used, the selection of which depends on the connection characteristics of a given location (large wind turbines can be connected to medium to high voltage overhead lines and medium voltage network, smaller to low to medium voltage network).

Equation 4

$$Spatial\ LCOE = \frac{\sum_{t=1}^{n} \frac{I_t * (1 + \text{topology factor}) + O\&M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

Other efforts regarding the assessment of energy potentials are presented in Paper IV, V and VI. These include the estimation of mini and small hydro power potential in developing countries, the estimation of the cost of generating electricity using solar photovoltaics and diesel generators.

4.2 Spatially explicit least cost set of technologies for universal access to electricity

An electrification programme is designed to provide (or advance) access to electricity to the people that live in unserved areas. In developing countries, the national or regional grid network does not supply electricity to most rural areas. Expanding the electricity network to sparsely populated areas can be economically challenging. To illustrate, the further a settlement is from the nearest grid, the higher the cost of supplying unserved settlements gets. At some point, a combination of low population density, large distance from the grid and difficult terrain makes off grid electrification options the technology of choice.

The second focus of this dissertation lies on comparing the cost of mature electrification technologies and providing least cost electrification plans in order to reach full access to electricity in developing nations. To do so, an Open Source Spatial Electrification Tool is introduced (OnSSET)[4]. OnSSET takes into account local resources' availability, infrastructure, economic activities and demand related parameters.

OnSSET is a bottom up optimization toolkit. This means it is a technology driven model, the objective of which is to achieve full access to affordable, reliable, sustainable and modern electricity for all by 2030 in the least cost manner. Furthermore, OnSSET is a complementary tool to existing energy planning models, which do not consider geographical characteristics related to energy. As compared to similar planning tools, OnSSET is the first spatial electrification tool that considers and compares a plethora of mature electrification technologies and accounts for a large number of spatial datasets to determine the least cost options for the entire unelectrified population across a country.

Paper IV introduces a GIS based electrification planning approach applied on Nigeria, which forms the basis of OnSSET. The use of GIS and remote sensing techniques is essential to derive resource and infrastructure related information that is either limited or absent. The identified datasets for the analysis can be split in four categories, as shown in Table 3.

Table 3: Identified datasets for electrification planning

Categories	Datasets
Resources	Wind Solar

[4] The model structure and methodology, the geospatial analysis, the incorporation of a cost model in GIS, as well as the largest part of the electrification algorithm and its development, the dissemination of the tool and the development of training material constitute author's contributions.

	Hydro Oil (+ transportation cost)
Infrastructure	Road network Transmission network Power plants Night-time lights
Economic activities	Mining and Quarrying sites
Demand side	Population density Population growth Administrative boundaries Urban/rural split

The electrification options are divided into three main categories (grid connected, mini-grid systems and stand-alone systems). These options are presented in Table 4.

Table 4: Technologies compared for energy access

Category	**Supply technology**
Grid connection (Grid)	National grid
Mini grid systems (MG)	Solar PV Wind turbines Diesel generators Hydropower
Stand-alone systems (SA)	Solar PV

	Diesel generators

Nigeria is split in smaller grid cells with spatial resolution of ca 2.5 km x 2.5 km. For each cell and for each technology, starting from the geospatial data presented above, the levelized cost of generating electricity is calculated. Four geospatial parameters are considered and are connected to the costs:

a. Level of electricity consumption: the amount of electricity that households are or will be provided (in case they are not electrified), measured in kWh/household/year.
b. Population density: measured in people/km^2
c. Local grid connection characteristics include distance to the closest existing and planned grid (km) and national cost of grid generated electricity (US$/kWh)
d. Local energy resources availability influences the cost of the various energy technologies. To illustrate, a higher wind power capacity factor would imply a lower cost of generating electricity ceteris paribus.

A decision algorithm is created in order to assess the suitability of each grid cell for grid connection. The algorithm was initially written in Visual Basic (VBA) (126) and has recently been converted to a much faster, more elegant and open source Python code using the Locality-Sensitive Hashing technique for Finding Nearest Neighbours (127). The conversion from VBA to a cost effective Python equivalent with reduced computational time requirements was the objective of UN's Electricity4All challenge, which I organized and led. The Python programming language was chosen, as it is an open source programming language and the scripting language of choice for GIS users[5].

[5] The most updated electrification algorithm can be found here: https://github.com/KTH-dESA/PyOnSSET

Box 1: Brief description of the electrification algorithm

> The electrification algorithm procedure is based on two separate, yet complementary processes. On the one hand, a GIS analysis is required to obtain a settlement table referencing each settlement's position – i.e., its x and y coordinates – and information related to demand, resource availability, infrastructure and economic activities. Night-time light datasets are used in combination with population density and distribution, the transmission and the road network in order to identify the presently electrified populations. The initial electrification status is listed as either 1 (electrified) or 0 (non-electrified).
>
> The algorithm calculates the cost of generating electricity at each cell for different electrification configurations based on the local specificities and cost related parameters. For each electrified cell, iterations through all unelectrified cells are performed to test if the conditions for their connection to the electrified cell are fulfilled. These conditions include (a) lower cost of generating, transmitting and distributing electricity as compared to other off grid technologies (b) not causing the total additional MV grid length to exceed 50 km if it is connected. If these conditions are verified, the settlement status is switched to electrified.
>
> In parallel, the algorithm stores the length of the additional MV lines that have been built thus far by the model to connect this new settlement. This is required to ensure all newly electrified cells comply with the 50 km limit for the length of MV lines. Further, this is also used to consider cost increases for each additional MV extension, due to the requirement to strengthen the previously built grid line.
>
> This process is repeated with the newly electrified cells until no additional cells are being electrified, and thus until all settlements to which the grid can be economically extended are reached. Settlements that are not connected to grid will get access to electricity through mini grid or stand-alone systems. This decision is based on a cost comparison process.

In this analysis, the electricity consumption levels were in agreement with the International Energy Agency to be 170 kWh/capita/year for rural and 350 kWh/capita/year for urban areas that are currently unelectrified. These levels refer to 2030, as this was the time frame of the electrification analysis.

Papers V and VI advance the methodology that was applied on Nigeria. Paper V introduces least cost electrification insights for Ethiopia, while Paper VI presents an analysis for all Sub-Saharan African countries. Advancements of Paper V include the spatial estimation of mini and small hydropower potential and the addition of two different electricity demand levels. On top of those additions, Paper VI complements with the use of Open Street Map data to determine supplementary transmission and power plant information. Further, this analysis accounts for various electricity consumption levels and current and future international oil prices. In this analysis, the costing of each technology considers the topological characteristics of the subjected area, e.g. elevation, proximity to road network, land cover, slope gradient and distance from substations affect the initial investment cost. Finally, coastline information is adopted in order to calibrate a heuristic for diesel costing.

4.3 The role of GIS in energy planning and energy access

Drawing information from all the published papers, this section accents the role of GIS in energy planning and energy access. Within energy planning, the geography of energy systems plays a vital role and makes the integration of GIS a powerful addition to the energy modelling toolkit. The integration of GIS in energy planning serves multiple purposes. The following three examples highlight the strength of using and analysing spatial data in energy planning.

1. GIS techniques enable filling data gaps in developing countries using remote sensing techniques. In papers I-III, an assessment of technical and economic wind power potential is carried out. Introducing and applying GIS based analytics facilitate the collection and generation of otherwise unavailable location specific and geographically disperse data (such as wind resource, infrastructure, restriction zones, population density as well as resulting potential energy yields, LCOEs and others). In papers IV-VI, other renewable energy potentials (solar and hydropower) are also enumerated.

2. Further, GIS calculations allow for the assessment of spatially explicit energy demand information. For instance, in papers IV-VI GIS techniques are used to derive location based population density, proximity to urban centres, and with the use of night time light data to determine electrification deficits to be met.

Thereafter, different energy access targets may be applied for urban and rural regions. The World Bank's Energy Sector Management Assistance Program (ESMAP) has already demonstrated that people's access to electricity cannot be understood as a binary issue of "connected"/"not connected" and have thus introduced a Multi-tier Framework for electricity access. This defines five tiers of access, each tier representing different levels of electricity services provided starting from basic lighting (lowest tier) to services that provide comfort, such as air-conditioning (Table 5) (16). The electrification deficit, together with the tier of access to be targeted allows the power demand to be estimated.

The same applies for energy resources and fuel costs. For example, GIS techniques are used to compare different geographically dispersed energy sources. Paper V examines how the penetration of diesel generators changes when other electrification solutions (such as stand-alone solar PVs) are introduced in the energy mix.

3. Moreover, GIS techniques can be used to demonstrate data in an easy to grasp manner via interactive maps and provide an effective science-policy interface. A plethora of insightful maps that can be communicated "at-a-glance" to the usually time-poor policy makers are presented in all papers, from resources, to technical wind energy potential yield to least cost electrification mixes and corresponding technologies and least cost spatially explicit LCOE etc. Such maps are provided in all outputs of this dissertation: papers I-VI.

Table 5: Mapping of tiers of electricity to indicative services[6]

Level of access	Tier-0	Tier-1	Tier-2	Tier-3	Tier-4	Tier-5
Indicative appliances powered	Torch and Radio	Task lighting + Phone charging or Radio	General lighting + Air circulation + Television	Tier 2 + Light appliances (i.e. General food processing and washing machine	Tier 3 + Medium or continuous appliances (i.e. Water heating, ironing, water pumping, rice cooking, refrigeration, micro wave)	Tier 4 + Heavy or continuous appliances (i.e. Air conditioning)
Consumption per capita and year (kWh)	-	8	44	160	423	598

4.4 Spatial data

Several spatial data at various resolutions were used throughout this thesis. Table 6 summarizes GIS datasets that were identified as useful for renewable energy resource assessment and electrification analysis in the studied regions. The category, type, spatial scope, resolution and the sources of the datasets are also provided.

[6] These consumption levels consider a certain efficiency level. Energy efficient appliances might decrease the consumption level for each tier.

Table 6: Spatial datasets for renewable resource assessment and electrification analysis[7]

Dataset source	Dataset	Category	Type of data	Spatial Scope and Proxy	Resolution	Study area
International Steering Committee for Global Mapping (105)	Urban built up areas	Demand side	Raster	Restriction	500 m	All[8]
Worldpop (106)	Population density	Demand side	Raster	Energy demand	1 km	Africa
Linard et al (107)	Population	Demand side	Raster	Demand projection	2.5 km	Ethiopia
Global Administrative Boundaries (108)	Administrative Areas	Demand side	Vector/ Polygon	Administrative levels 1 to 3	-	All
National Centers for Environmental Information (109)	Night-time light	Infrastructure	Raster	Energy demand	1 km	Africa
Socioeconomic Data and Applications Centre (SEDAC et al., 2013)	Road network	Infrastructure	Vector/Line	Distance to road	-	Africa
African Development Bank (110)	Transmission network	Infrastructure	Vector/Line	Distance to grid	-	All
International Energy Agency World Energy Outlook ((111)	Transmission network	Infrastructure	Vector/Line	Restriction	-	India
Open Street Maps (112)	Transmission network	Infrastructure	Vector/Line	Distance to grid	-	Africa
United States Geological Survey (113)	Mining reserves	Infrastructure	Vector/Line	Economic activities	-	Africa
African Development Bank (110)	Power plant location	Infrastructure	Vector/Point	Point location	-	All
Open Street Maps (112)	Power plant location	Infrastructure	Vector/Point	Point location	-	Africa
Joint Research Centre (114)	Travel time to big cities	Infrastructure /Resources	Raster	Transport cost	1 km	All
Consultative Group for International Agricultural Research (115)	Elevation map	Resources	Raster	Restriction	90 m	All

[7] In this thesis all spatial datasets use WGS84 World Mercator as coordinate system (104)
[8] “All” refer to all studied areas in this thesis.

International Steering Committee for Global Mapping (105)	Agricultural zones	Resources	Raster	Restriction	500 m	All
Goddard Earth Sciences Data and Information Services Center (116)	Wind speed	Resources	Raster	Wind power potential	55 km	All
International Steering Committee for Global Mapping (105)	Forest areas	Resources	Raster	Restriction	500 m	All
Consultative Group for International Agricultural Research (115)	Slope	Resources	Raster	Restriction	90 m	All
National Renewable Energy Laboratory (NREL, 2003)	Solar irradiance	Resources	Raster	Solar availability	40 km	Africa
Consultative Group for International Agricultural Research (115)	Digital elevation map	Resources	Raster	Water flow direction	90 m	All
Joint Research Centre (117)	Global Streamflow Characteristics Dataset	Resources	Raster	Runoff	14 km	Africa
Hydrological data and maps based on Shuttle Elevation Derivatives at multiple Scales (HydroSHEDS, 2013)	Global river network	Resources	Vector/Line	Hydropower potential	-	Africa
Authors' calculations (contributed to the methodology development)	Small and Mini hydropower potential	Resources	Vector/Point	Point location	-	Africa
United States Geological Survey (118)	Water bodies	Resources	Vector/ Polygon	Restriction	-	All
Protected planet (119)	Protected areas	Resources	Vector/ Polygon	Restriction		All
Natural Earth (120)	Coastal areas	Resources	Vector/ Polygon	Distance to nearest coast	-	Africa
Feng et al (121)	Inland water bodies and restriction zones	Resources	Vector/ Polygon	Restriction	-	All

5 Results and discussion

This chapter is divided into two major parts. The first section reveals the most important results from each paper in order to answer the three interrelated research questions of this dissertation. The second part consists of more general discussions. These provide insights on the approaches and methods introduced, developed and applied in this research in an overarching manner and on how the dissertation fits into the literature and its contribution to the research topic. The techno-economic assumptions behind the presented results can be found in the appended papers.

5.1 Results

5.1.1 Spatial techno-economic potential of renewable energy resources

In paper I, several socio-economic and geographic layers regarding the localization of wind farms were combined in order to obtain the overall wind power availability map, shown on the top panel in Figure 4. About 24% of the studied area becomes available for wind power installations. It is noteworthy that an additional restriction that requires wind farms to be installed within 100 km from the transmission grid reduces the available area to ca 16%. Combining the overall availability map with the technical performance of a wind farm and the wind speed distribution, the technical wind energy potential is estimated and represented on the bottom panel of Figure 4. The total estimated potential of the continent reaches 72 PWh. After applying the additional grid restriction, this figure drops to less than 45 PWh. This falls further to 31 PWh if capacity factors larger than 20% were to be considered as economically acceptable (128,129). Still this amount is significantly larger (ca 42 times higher) than the total final electricity consumption on the continent in 2012 (130).

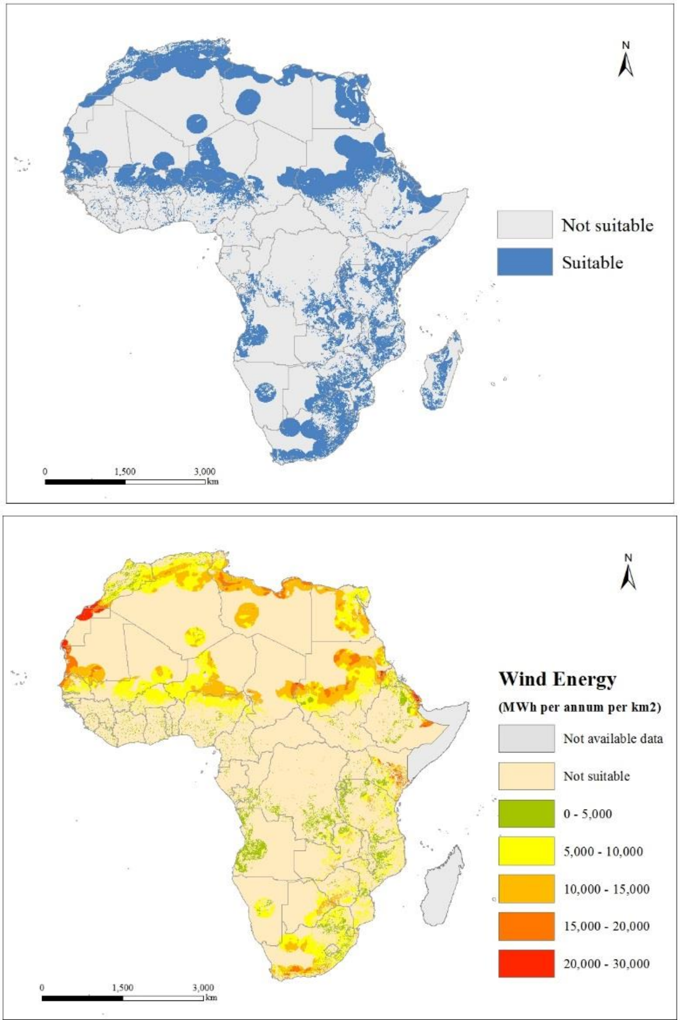


Figure 4: Availability map for wind power installations (top) and wind energy potential (bottom)

A summary of the potential yield per African power pool (see Figure 5) shows that the highest potential is realized in the North African Power Pool, followed by the South and East. Power Pool. The Central African countries signify the least wind power potential.

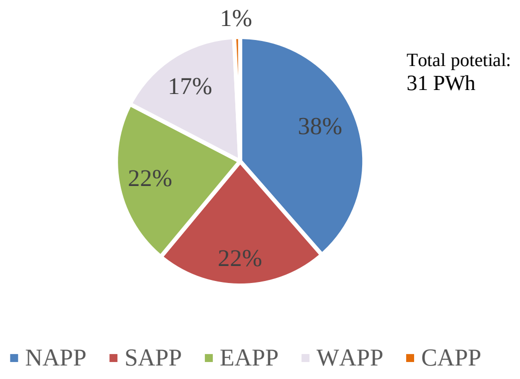


Figure 5: Technical wind power potential per African power pool

Likewise, in paper II, the wind power potential is estimated in India. In this case though, economic indicators are added to evaluate the feasibility of wind power projects. The levelized cost of wind generated electricity is calculated on a spatial basis and ranges between 57 and 100 USD/MWh for the "available" locations with capacity factor greater than 20% (Figure 6). These values place wind power in a competitive position in the Indian electricity market, since the present cost of generating electricity in the country reaches 115 USD/MWh (111). Besides the LCOE, the accumulated net present value of all costs is also estimated. The total costs reach roughly 1.7 trillion USD (Figure 7).

In the same figure, a direct relation between net present value of all costs and the wind energy yield is observed. The higher the yield, the higher the needed capacity and the costs. However, this is not always the case. The costs in Rajasthan appear higher than in Gujarat despite the fact that the wind energy yield does not follow the same pattern. This occurs thanks to higher capacity factors realized in the state of Gujarat, which implies that a smaller number of wind turbines would be needed to generate the same electricity as in Rajasthan. The total costs and the estimated wind energy yield can be used as input while designing a viable Feed-in Tariff scheme, which will attract private investments and possibly increase the penetration of wind power in the energy market of the country.

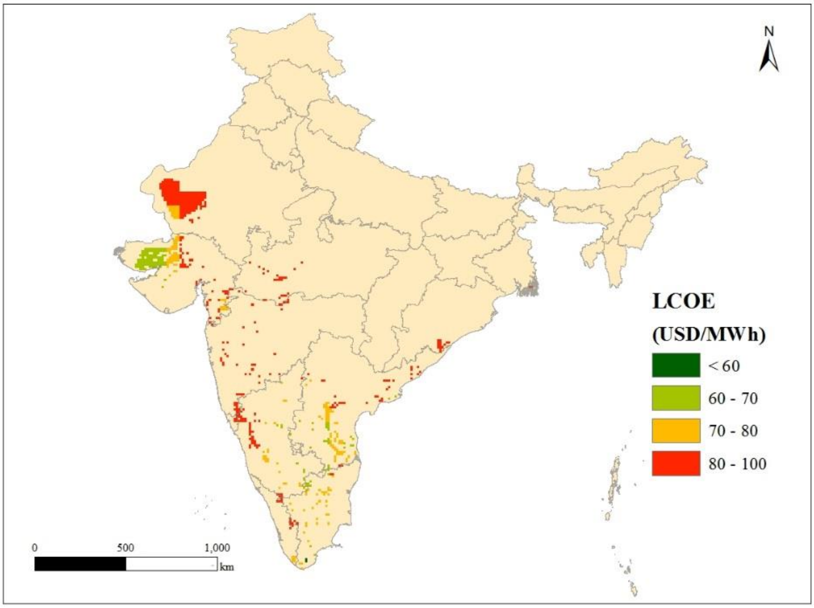


Figure 6: Geospatial levelized cost of wind generated electricity in India (capacity factor greater than 20%)

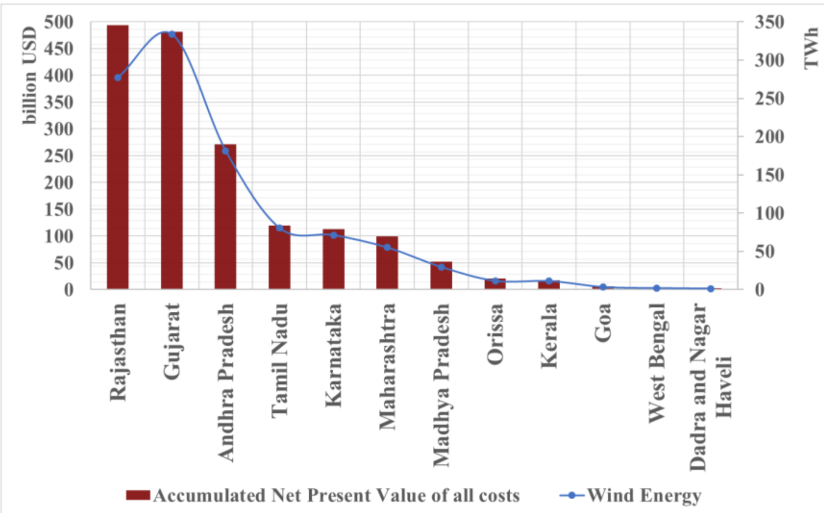


Figure 7: Accumulated Net Present Value of all costs and Wind Energy Potential

The methodology developed for India in Paper II is also applied on the African continent. Paper III takes into account all the previously considered geographic and technical constraints and adds a topology factor in order to assign an incremental capital cost in locations with specific characteristics. For instance, the existence and quality of the road network, as well as the land cover type influence the construction cost of a wind farm. The results of the levelized cost of wind generated electricity are presented in Figure 8 (in 5km resolution) taking into account the overall suitability map and areas that indicate a capacity factor greater than 20%. The GIS analysis indicates that wind electricity can be generated at a cost that varies between 0.04 and 0.16 USD/kWh. Not only the wind resource regime but also the spatial characteristics of an area influence the cost of wind generated electricity. Areas with high wind resource regime and close to the transmission and road network indicate lower LCOE as opposed to remote areas with similar resource availability.

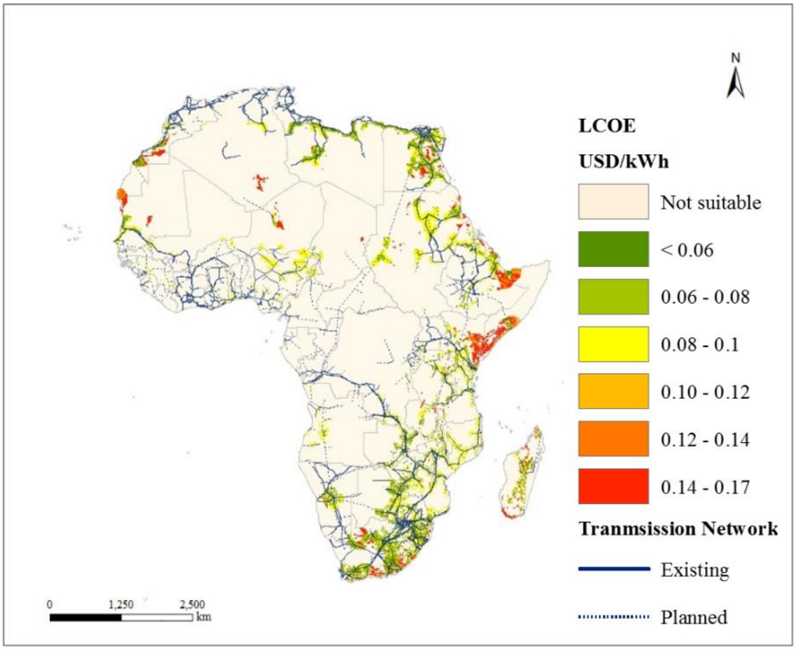
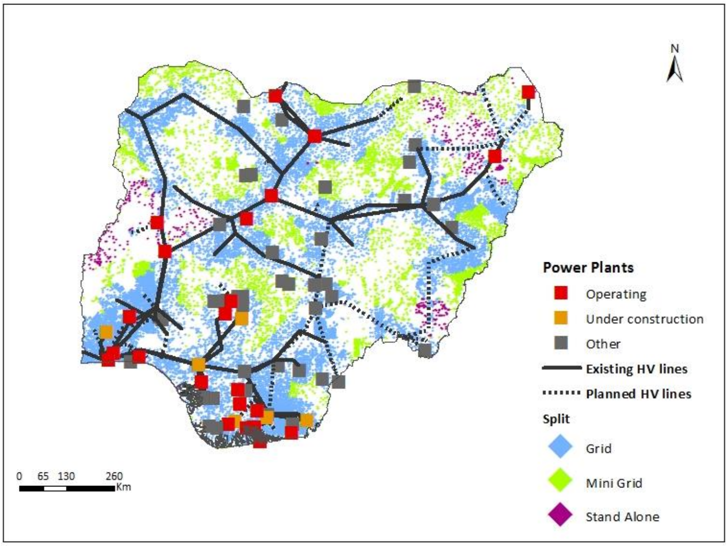


Figure 8: Spatially explicit levelized cost of wind generated electricity in Africa – V112 turbines for locations close to the Transmission Network, V44 turbines for locations more than 50 km away from the Transmission Network

5.1.2 Spatially explicit least cost set of technologies for universal access to electricity

The most cost-effective way to expand electrification varies widely between and within countries in Sub-Saharan Africa, as well as changing over time as income and consumption patterns evolve. In papers IV-VI, a GIS based approach is introduced and applied for electrification planning in different case studies. Detailed spatial analyses undertaken in these three papers illustrate how a range of geographic factors affect the least cost technology mix needed to achieve universal access. In this section, a representative selection of results is presented.

The electrification planning results of the Nigeria case study are demonstrated in Figure 9 (Paper IV). It is apparent that grid-based connections are preferred for areas with higher population density and within a certain distance from the transmission network, thus in areas with high consumption levels (depicted in blue on the top panel of the following figure). For about 85% of the newly electrified population, the connection to the main grid constitutes the most economical solution. Mini grids and stand-alone systems with a 15% share of the new connections play also an important role in providing access to electricity in rural and remote areas. The bottom panel of Figure 9 shows the potential cost of providing electricity in different regions in Nigeria. This includes considerations related to road and transmission infrastructure, population density, diesel cost based on distance from distribution stations, grid costs as a function of distance from the main grid, grid strengthening costs, geospatial renewable energy potentials. The LCOE ranges from 0.15 US$/kWh for areas already connected to the national grid to 1.4 US$/kWh for remote areas with low population density electrified by stand-alone diesel generators or solar PVs.



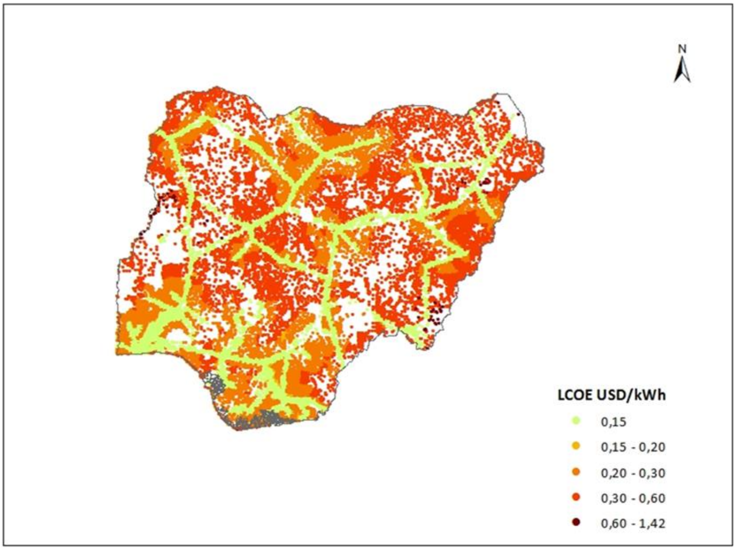
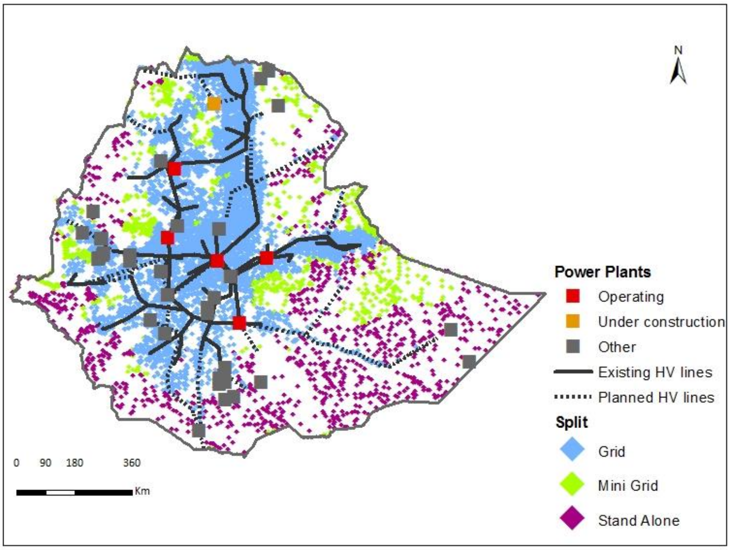


Figure 9: Least cost electrification mix and major generation and grid infrastructure (top) and spatial levelized cost of electricity (bottom) in Nigeria (170 kWh/capita/year for rural and 350 kWh/capita/year for urban areas that are currently unelectrified)

In Ethiopia too, a significant proportion of the population lives in areas that can be best connected through the grid reaching ca 93% of the new connections (Paper V). But the overall population density of Ethiopia is considerably lower – the number of people per square kilometre (97) is half that of Nigeria (195) in 2014 (131) – meaning that mini grid and stand-alone options play a prominent role in remote areas depicted in green and purple respectively in Figure 10. LCOEs range from 0.12 US$/kWh in areas already connected to the national grid to 1.74 US$ in remote areas with low population density.



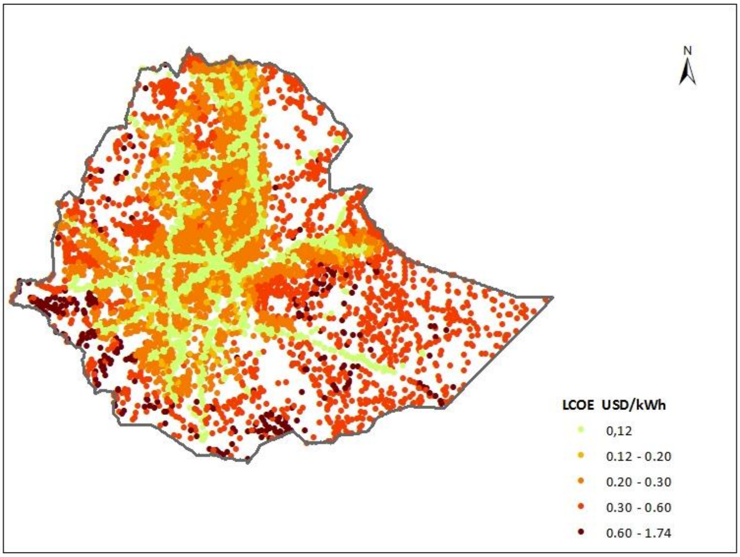


Figure 10: Least cost electrification mix and major generation and grid infrastructure (top) and spatial levelized cost of electricity (bottom) in Ethiopia (150 kWh/capita/year for rural and 300 kWh/capita/year for urban areas that are currently unelectrified)

Similarly, least cost electrification options for 2030 were calculated and mapped for about 26 million locations in Sub-Saharan Africa, considering a grid cell size equal to the given population density GIS datasets (ca 1km x 1km) (see Figure 11). For the 5th Tier of access, the majority of the African population (78% of the new connections) reaches access via grid connections. Mini grid systems take up large areas (16% of the new connections) while stand-alone systems are the technology of choice in sparsely populated and remote areas and provide access to ca 6% of the newly connected population.

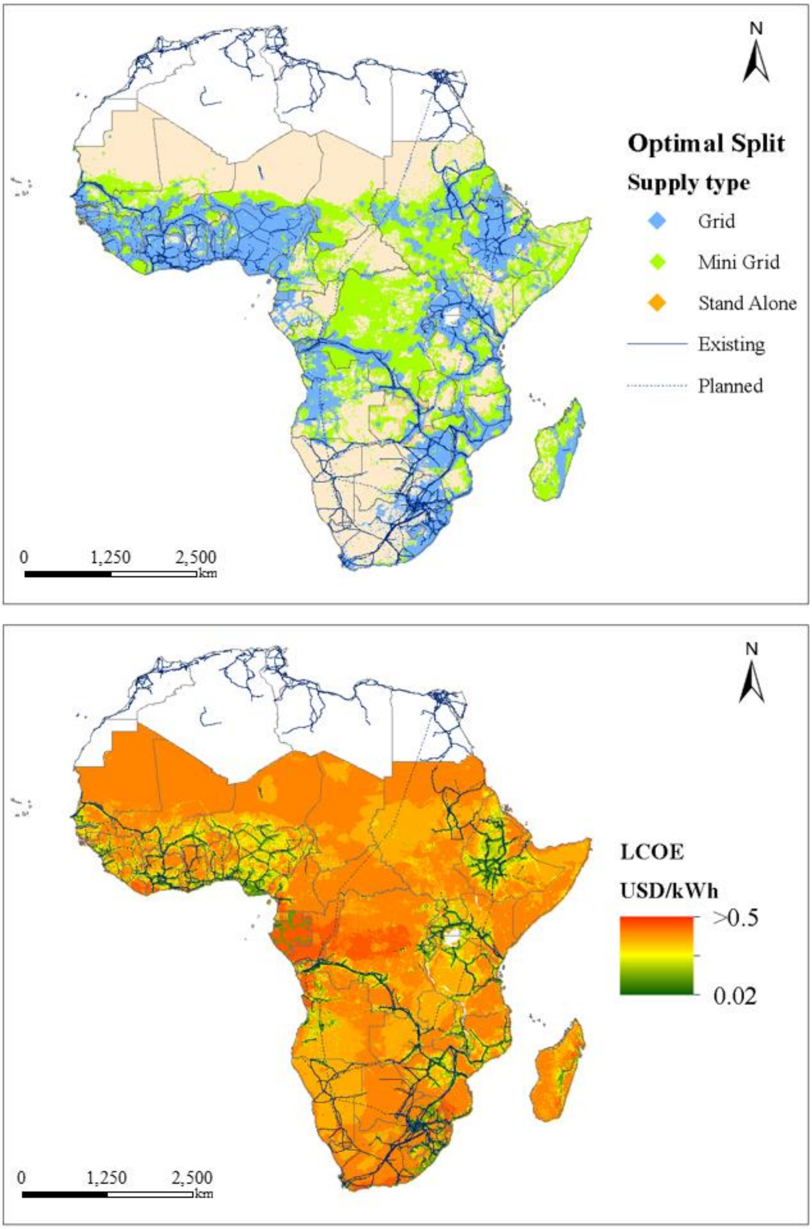


Figure 11: Least cost electrification mix and major grid infrastructure (top) and spatial levelized cost of electricity (bottom) in Sub-Saharan Africa (for high diesel cost and Tier 5)

Not only the access type but also the specific technologies are available on a spatial basis, the spatially explicit cost optimal electrification technology is mapped for Tier 5 – higher diesel price in Figure 12.

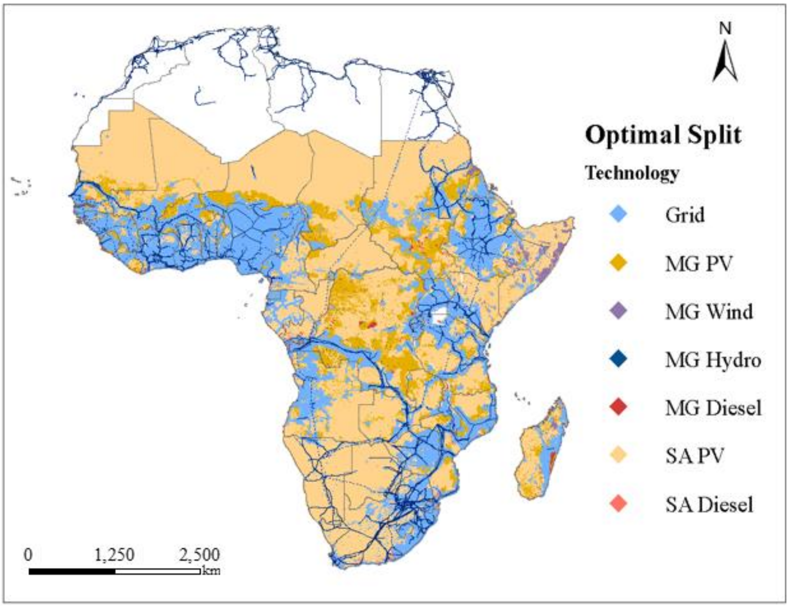


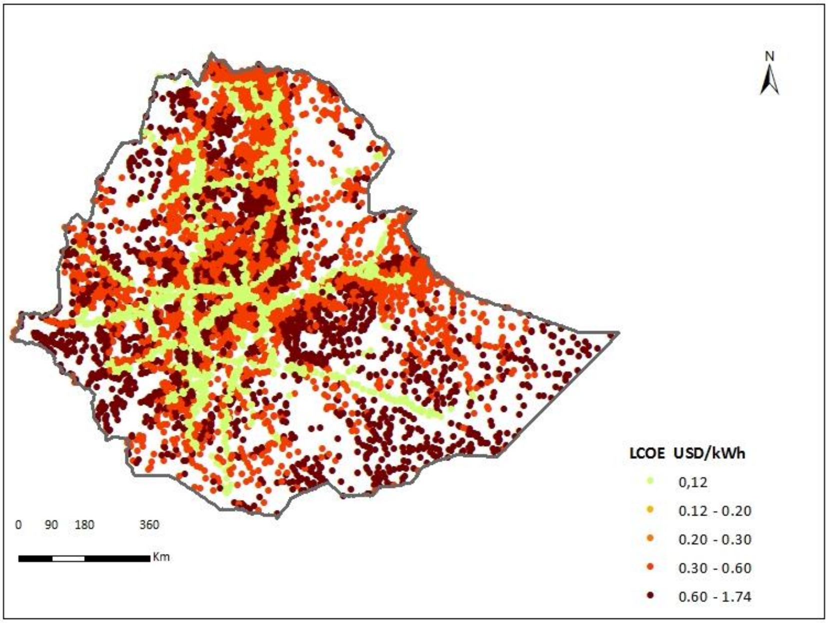
Figure 12: Least cost electrification technology for high diesel cost and Tier 5 (MG stands for Mini Grid systems and SA for Stand Alone)

5.1.3 The role of GIS in energy planning and energy access

The results presented in the previous paragraph refer to specific scenarios for each case study regarding the energy access target, oil prices etc. GIS enables the possibility to assess how different scenarios influence the technology selection and therefore the total investment needs for universal electricity access. GIS help planners answer questions such as: how does technology mix and the corresponding cost of generating electricity vary if a range of technologies is available in the off grid market? In what geographical locations would the additional technologies be cost efficient and how does the oil price affect the electrification mix? How would the technology mix change with increasing electricity consumption levels?

In the case of Ethiopia (Paper V), the importance of geospatial electrification planning is demonstrated by two additional scenarios. One scenario considers only diesel stand-alone technologies to electrify population that lack access to electricity nowadays, while the other scenario considers as an additional option to invest in stand-alone solar systems (see Figure 13). The deployment of stand-alone PV solutions decreases the LCOE in some areas as compared to stand-alone diesel generators. Stand-alone PV technology would be more viable for roughly 23 million people. In case grid extensions and mini grid technologies were to contribute to the electrification mix of the country, only a little more than 0.6 million people would be connected to stand-alone systems. In Figure 14 the weighted mean LCOE for Ethiopia is presented [9]. It is noteworthy that LCOE drops from 0.30 USD/kWh (only stand-alone diesel generators scenario) to 0.27 USD/kWh (stand-alone diesel and solar PVs). If all electrification options are considered (grid expansion, mini grid and stand alone systems), LCOE is shortened even further to 0.12 USD/kWh.

[9] Weighted in terms of population density.



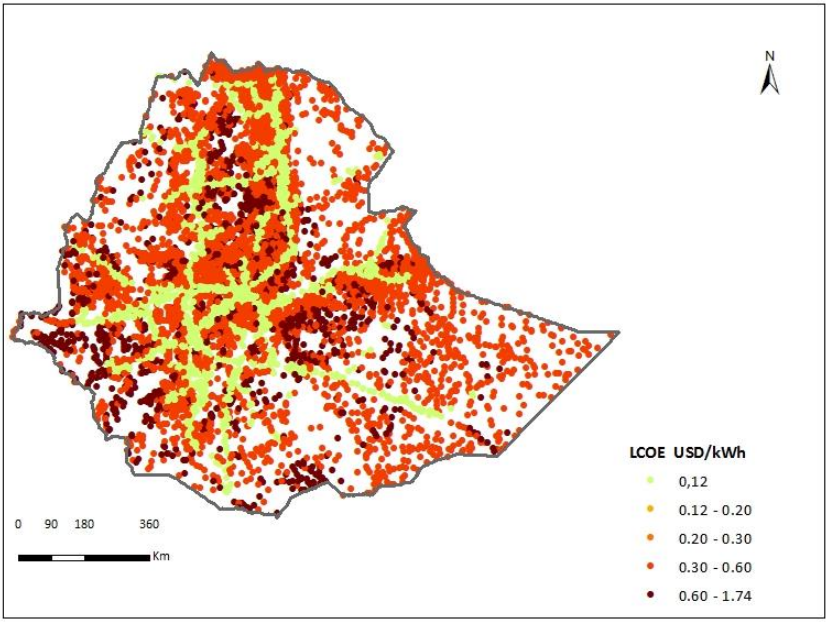


Figure 13: LCOE for the electricity access targets 150 (rural)-300 (urban) kWh/capita/year in Ethiopia [top panel: Population already electrified is grid connected and the rest are electrified by Stand Alone Diesel, bottom panel: Population already electrified is grid connected and the rest are electrified by Stand Alone Diesel and PV]

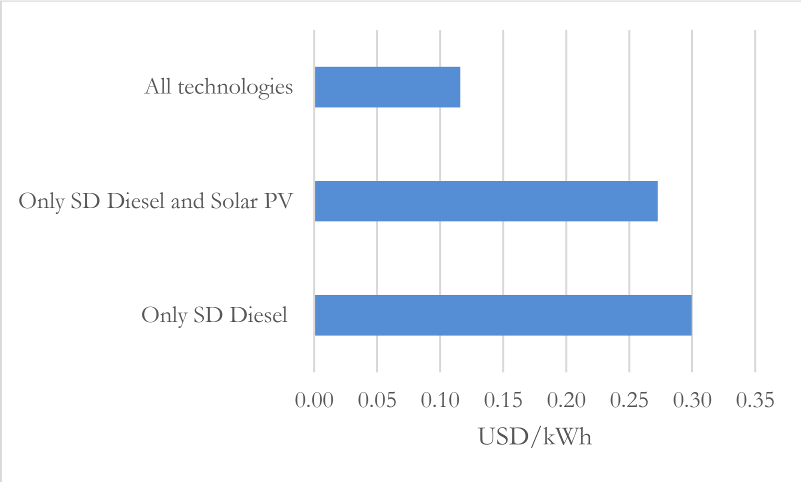


Figure 14: Weighted mean LCOE for different technology configurations

Furthermore, different levels of electricity consumption influence the technology decision. Several scenarios were evaluated with regards to electrification planning for Sub-Saharan Africa. Figure 15 illustrates results for a postulated electrification of the sub-continent by 2030 for different levels of electricity demand (Tiers) and oil prices. The maps clearly demonstrate the impact of the different tiers per cell. For Tier-1, electrification is accomplished by grid-based electricity (settlements located close to previously electrified villages and transmission lines) and, predominantly, by stand-alone systems elsewhere. Mini grids play a minor role only. For Tier-3, grid-based electricity is expanded as higher demand makes grid connection a viable proposition (to the detriment of stand-alone supplies). Demand levels of Tier-5 further expand grid deliveries to settlements but mini grid have become economically quite attractive. High diesel prices boost further grid-based electricity and mini-grids (see bottom right hand side of Figure 15). Stand-alone systems play a key to electricity access for all. By 2030, large regions are projected to remain sparsely populated and stand-alone systems are the only economically viable electrification option.

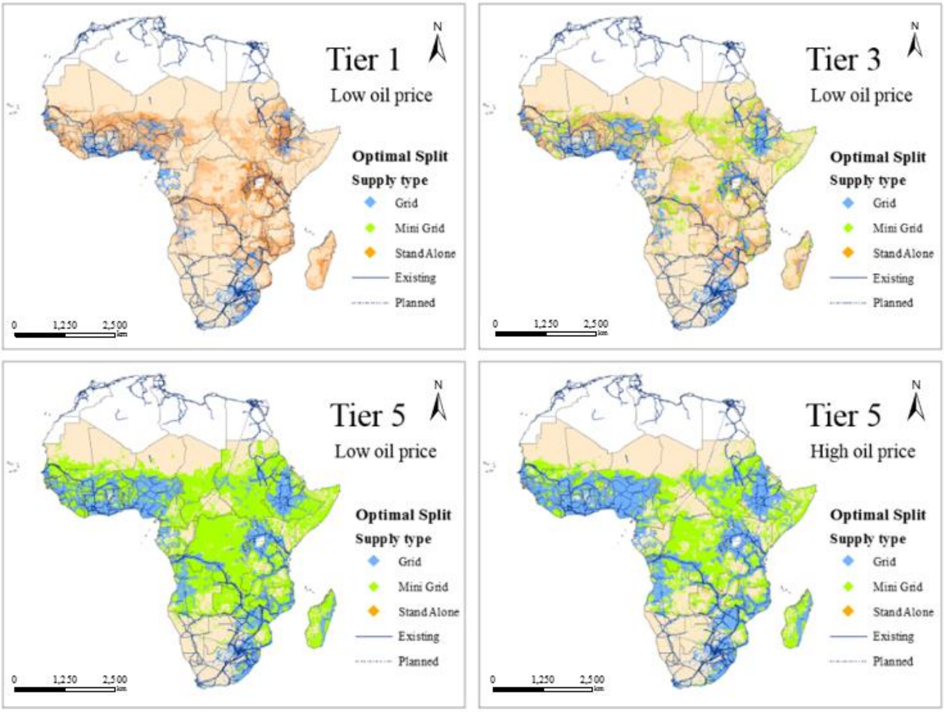


Figure 15: Least cost electrification mix for low diesel cost and Tier 1 (top left), 3 (top right) and 5 (bottom left); and high diesel cost and Tier 5 (bottom right).

At high diesel prices and higher tiers, mini-grids and stand-alone systems supplied by renewables make an entry. These move from predominantly diesel to solar, hydro and wind power systems. The relative population/technology transitions by Tier and diesel price is well illustrated in Figure 16.

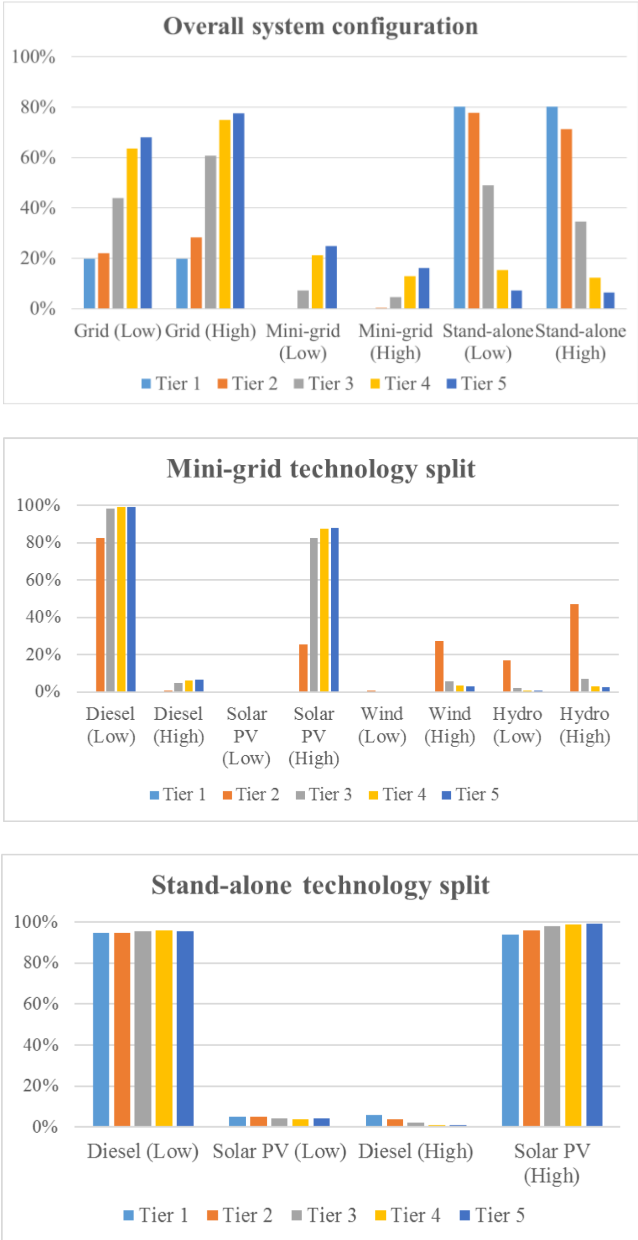
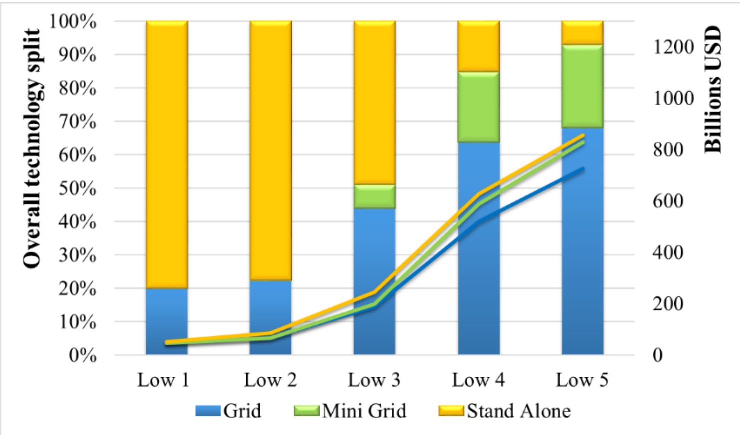


Figure 16: Overall system configuration (top); mini-grid technology choice (middle); stand-alone technology choice (bottom).

So least cost electrification mix has been determined but is this an economically feasible solution? The minimum cumulative investment requirements for electrification of Sub-Saharan Africa by 2030 amount to 50 billion US$ for low diesel prices and the lowest electrification level, whilst the maximum investment for universal access reaches 1.3 trillion US$, for the higher diesel price and the highest tier of electrification. Included are the capital costs for grid-connected power plants, transmission and distribution infrastructure as well as for all off-grid systems (stand-alone and mini grid technologies). A summary of the investment needs and the technology split is shown in Figure 17. The investment needs in the low diesel scenario range from 50 to roughly 850 billion US$, depending on the Tier of access. Whilst for the higher diesel price the corresponding values stand at 64 billion US$ and 1.3 trillion US$ respectively. This occurs as higher diesel prices increase the system costs and allow relatively more expensive, (non-oil based) grid and mini grid systems competitive.



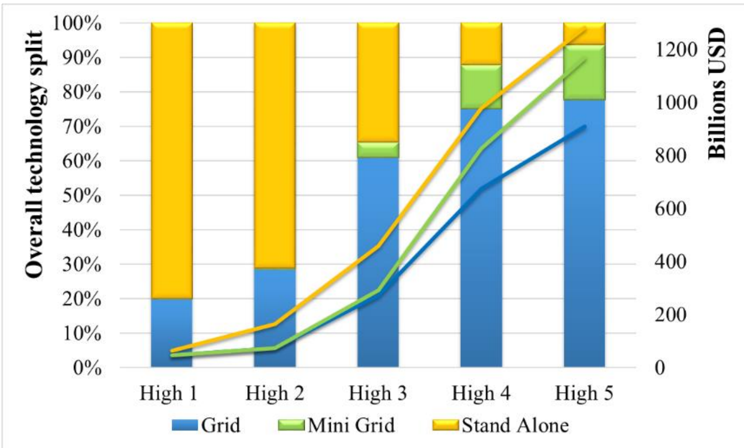


Figure 17: Technology split, in bars, and overall investment needs, in lines, for universal access by 2030 for low diesel (top); and high diesel (bottom) costs.

This analysis was initially carried out at 10 km resolution and formed the basis of United Nations Modelling Tool for Sustainable Development "Universal Access to Electricity" and the associated Online Electrification Interface (132)[10]. It is worth stating that the investment needs to reach full access to electricity on the sub-continent between the coarser resolution analysis (10 km) vs the corresponding figures at 1 km in Paper VI differ just about 4%, which makes the Online Interface a valuable tool for initial electrification planning purposes.

5.2 Discussion

Many energy system models are largely decoupled from the real world in a geographic sense. They disregard the actual geographic relationships among the various components and parameters that form an energy system. Often, this is 'good enough'. But in certain circumstances much is to be gained by their integration into GIS. A relatively comprehensive coupling constitutes an important contribution of this work.

Starting with assessing the technical and techno-economic potential of renewable energy technologies in Africa and in India respectively, several geographic and technical parameters were taken into account while estimating the potential energy yield of wind power. These values shall serve as an upper limit constraint for the potential penetration of a particular technology while searching for the optimal energy mix in a region in an energy system model and/or feed electrification planning studies.

OnSSET, the Open Source Spatial Electrification Tool has been designed in order to identify least-cost options to electrify areas currently unserved by grid-based electricity. Models addressing electrification and access need consistent energy-related data and information on a geographic basis such as settlement sizes and locations, distances from existing and planned transmission infrastructure, electric grid network, economic activities and local renewable energy flows. This information in most developing countries has been missing. This paucity of information has hampered energy planning in Africa in general and particularly electrification of remote rural areas. The situation has essentially improved with increasing availability and application of GIS and remote sensing techniques which can provide information that has not been accessible previously. Integrating GIS and

[10] The online interface is available at: http://un-desa-modelling.github.io/electrification-paths-visualisation/

energy system modelling helps identify the most effective electrification strategy on a geospatial basis.

Such a pairing has several limitations though. Both energy systems models and GIS processes are highly complex in terms of data collection and model approximations. This complexity is accompanied with heavy computational requirements due to the high number of necessary datasets used to obtain fine-grained results. Moreover, the integration of a variety of heterogeneous data structures poses a major challenge. Data availability and accessibility, proprietary datasets, singular data integration methods and lack of standardized format of data exchange constitute substantial problems. Further, an additional challenge that comes along with restricted data availability is the inhomogeneity in the level of granularity. This calls for aggregation and disaggregation mechanisms resulting sometimes in misleading representation of information.

With no established mean of dissemination of open data through platforms, practitioners have been forced to regularly aggregate data. It is therefore crucial to create ways for practitioners to share aggregated, updated and publicly available data reducing high transaction costs of data aggregation. This will further help mainstreaming the use of geospatial analytics for the energy sector. Moving towards open data, the presented research work has contributed with several datasets to Energydata.info, an Open Energy Data platform, recently launched by the World Bank Group (133). This constitutes a platform for sharing data, visualizations and analytical tools that are relevant to the energy sector.

Note that the performed analyses included in this dissertation are "as good as the data" and the results are only indicative. To illustrate, the selection of the restriction zones for the localization of wind power plants is a result of an extensive literature review. However, country specific siting restrictions might influence the output of the analysis (see (66). Other uncertainties in the analyses are mentioned in the appended papers.

6 Conclusions, Future Research and Impact

This chapter presents the overall conclusions of this thesis, along with recommendations for future research and an elaboration on the impact of this work in the subject field.

6.1 Conclusions

The methods developed in this thesis, from resource mapping to electrification analysis, allow analysts to improve upon the over-simplified dichotomy between on- and off-grid systems and can already provide invaluable support to policy and decision makers on least-cost electrification strategies. Most importantly, the methods (and the resulting Open Source Spatial Electrification Tool, OnSSET) specifically quantify the needs of the energy poor and offer insights. Numerically, the developed tool accomplishes the SDG-7 electrification target by 2030. It provides an outlook on the least-cost technology mix and on the associated investment requirements. But it does not implement the identified strategies nor does it provide the necessary finance. It highlights the challenges before policy and decision makers charged with the implementation of SDG-7. Moreover, it allows the analysis of trade-offs between competing demands on financial resources and thus assists in a prudent prioritization of the available financial resources. It is worth noting that between 1990 and 2010, the number of people with access to electricity has increased by 1.7 billion without a definite target of universal electrification (134). Now that we have the targets and the technological means to achieve these targets, a development plan can be set in place to achieve universal access to electricity.

Additions to the literature made in this thesis are summarized in the following table. These additions were the first of their kind at the time of publication.

Table 7: Academic contributions

New insights
• This thesis improves upon former simplified analytical dichotomy between on- and off-grid systems by comparing the two in cost terms after considering the local energy-related characteristics of a given area • The methods developed in the thesis allow for the development of rapid cost effective electrification plans with minimal resource and computational requirements as compared to existing electrification planning tools that are time-, data- and resource- intensive. • Furthermore, applications included in this thesis show that increased granularity added marginal value in two instances investigated in Sub Saharan Africa (a comparison of investment needs is carried out between an analysis at 1 km vs 10 km analysis).
New GIS based energy-related data calculated for individual countries and continents
These datasets were added to the literature: • Improved granularity in continent wide technical wind power potential in Africa. This was accomplished by using the best available spatial data at the time of writing. • Geospatially referenced cost of wind generated electricity throughout Africa and India. • Geospatially referenced electrification data for individual countries and regions. Such analysis was initially carried out for Nigeria, considering highly granular localities (2.5 x 2.5 km) compared to a previous study that only focuses on the local government areas in the country. Similar analysis was then carried out for the first time for Ethiopia, and ultimately for Sub Saharan Africa. The latter was undertaken both at coarse granularity (10 x 10 km) and at higher resolution levels (1 x 1 km). These spatially explicit figures include: o Least cost electrification option mix consisting of 7 configurations (Previous studies considered 2 to 4 electrification configurations). o Cost estimates for the supply of electricity to all locations in Africa with no access to electricity (Previous studies use lower granularity and/or limited number of GIS data and use a limited grid expansion algorithm).
New GIS based composite methodologies developed to accommodate new data

A new methodology was developed and applied to compare multiple local resources and resulting electrification configurations at various levels of granularity across a country (Nigeria, Ethiopia) and across a continent (Sub-Saharan Africa). This was novel as it:

- Is the first spatial electrification approach that considers and compares a plethora of mature electrification options.
- Accounts for a large number of spatial datasets to determine the least cost options for all unelectrified population across a country.
- Is soft-linked with a bulk electricity expansion model for all Africa. That allowed dynamic and endogenous price evolution associated with grid based costs. Other efforts assume an exogenous price for grid based electricity.

New aggregate electrification cost estimates

At an aggregate level, electrification insights were developed for every Sub-Saharan African country. These data include new connections, investment needs and associated generation capacity needs and are enumerated for:

- Different Tiers of electricity access (and is the first instance to do so).
- Seven electrification options in terms of technology split and costs and
- For current and projected oil prices.

While actual electrification routes may differ, this work provides a range of investment needs for achieving universal access, which can be used to inform decision and policy making.

New ICT infrastructure

Analysis and code have been made available online as the Open Source Spatial Electrification Tool (OnSSET). OnSSET is a first of its kind as it:

- Is written in an open source programming language in order to allow other users to modify the code according to their requirements
- Is calibrated for the use of open data and designed in a modular format in order to allow other users to replace with better data (and proprietary) based on their sources.
- Being open, it has since benefited from several contributions external to this thesis that have resulted in improved processing times etc.

Impacts

This thesis work and the OnSSET tool developed by it (and later contributed to by others) has demonstrated the importance of opening energy modelling to the open source community as it:

- allows additions made by external contributors, such as the UN's Electricity4All challenge (135,136)
- enables users to repeat an analysis as the code and data sources are publicly available
- allows users to carry out new applications and further develop the tool.

The developed tool has since been used for electrification planning analysis and capacity building activities by:

- International organizations, such as the World Bank, the International Energy Agency (IEA), United Nations Department of Economic and Social Affairs (UNDESA), United Nations Development Programme (UNDP)
- Industry, such as ABB
- Governments, such as the governments of Afghanistan and Ethiopia

The developed tool is also used in academic analysis and studies have focused on several countries in developing Africa and Latin America.

6.2 Recommendations and Future Research

With the increasing importance of GIS in energy planning and the improved computational capabilities, the further use of aggregated, frequently updated and freely accessible datasets will be fostered and will constitute a key element to support energy access. In this sense, some enhancements in the presented methodologies would also improve the quality of the results. The estimation of renewable energy potential is shown to be a significant parameter in the energy planning equation. It is therefore recommended that renewable potential estimations be validated and calibrated with ground level measurements. Furthermore, geospatial assessments should comply with country specific RE localization legislation when accounting for exclusion/restriction zones. Additional GIS layers should be considered while estimating the cost of generating electricity from renewable energy technologies. Capital investments vary for a specific technology between and across countries. A location specific transportation cost could be added using travel time and road infrastructure maps.

The least cost electrification mix is shown only for the end year of the analysis. The electrification mix and status in the meantime is not accounted for. To do so, electrification expansion determinants should be considered, such as achieving equity among regions by reaching certain electrification rates at a certain time and/or a certain amount of population gains access based on the proximity to the road network, as the latter influences the prioritization of investments.

Intermittency is not properly accounted for in the model. To illustrate, energy demand and supply profiles might differ from one location to another. Load profiles and renewable's intermittency should be accounted for. Here lessons can be learnt from the conventional energy system models.

The inclusion of additional technologies in the electrification mix constitutes one of the major next steps of the electrification planning toolkit. Hybrid configurations, such as solar-diesel, wind-diesel, hydro-diesel should be added in the technology mix as new electricity supply options. Regarding the electricity demand, it is suggested that other geospatial data are used to identify centres with human activities and linked to income and demand level. Such data may include night-time light, poverty rates, mobile coverage as introduced by (77,137–139). The mapping of urban growth is also essential to account for future socio-economic changes and associated electricity demand levels (140). The demand should also include other productive uses of electricity that boost income and welfare. These activities are typically in the sector of agriculture, rural enterprise, health and education.

The open source nature of the developed tool allows interested energy experts from African countries (and from other parts of the world) to refine the model's resolution or explore additional scenarios. Most importantly, the analysis needs to be carried out at national or subnational levels integrating the full representation of a country's centralized electricity system and the country specific electrification strategies. Such an integrated approach would constitute a powerful analytical and planning tool.

Finally, the magnitude of benefits associated with access to electricity should be documented and quantified. An indicator that accounts for the social dimension of energy planning should be introduced and incorporated in the developed toolkit.

6.3 Impact of the thesis work

This thesis has illustrated that GIS is an increasingly used tool in electrification planning. Its implementation can have considerable advantages in electricity access efforts throughout the world. In countries with low electrification rates, energy planning through GIS can provide an effective tool to map a multitude of parameters such as existing grid infrastructure, population density, climatic conditions and resource availability for renewable energy deployment. The work presented in this thesis aims at having a significant contribution to electrification planning approaches and energy resource assessments using GIS.

In the policymaking arena, electrification planning is often captured by private consultants' analytical infrastructure. I designed OnSSET aiming for an open source and modular format in order to allow other users to build and modify the code according to their requirements and sources. In fact, the development of OnSSET has demonstrated the importance of the open source community. The latter contributed to the enhancement of OnSSET through the completion of UN's Electricity4All challenge.

Besides the involvement of the open source community, a number of channels have been used in order to disseminate the results of this thesis.

To begin with, this work features in several high impact peer reviewed journals and shared with practitioners and energy planners that could obtain significant insights from those. Moreover, the work is included in numerous cutting-edge publications. To name a few, results reported in this thesis have been included in some of the world's most important energy-related publications, such as the IEA's World Energy Outlook (2014 and 2015), IEA's and World Bank's Global Tracking Framework (2015) and World Bank's Status of Energy Access Report (2017).

Furthermore, the developed tool OnSSET features as the main tool for estimating the investments needs to achieve universal access in United Nations Modelling Tools for Sustainable Development[11]. The website was launched in February, 2016 at the Headquarters of United Nations in New York. It provides an interactive platform for comparing seven electrification options on 44 Sub-Saharan African and 10 Latin American countries in ca 10 km grid resolution. Results are presented for 30 pre-defined scenarios (5 different tiers of electricity, 2 diesel prices, 3 costs of grid electricity). In the results section, the cost of generating electricity, investment needs, the optimal technology mix and other critical figures regarding electrification planning are included. Country summaries are also available. This platform has attracted interest from national authorities in developing countries, planners, practitioners and researchers.

Likewise, OnSSET has been used to develop national high resolution (1 x 1km) dynamic least cost options plans for universal access to electricity in Nigeria, Tanzania and Zambia[12]. A web-based open source application was developed in collaboration with the World Bank that allows the users to select among various scenarios regarding levels of electricity consumption and spatially related fuel costs and identify the least cost electrification technology. In addition, the developed application makes the underlying

11 See http://un-desa-modelling.github.io/electrification-paths-visualisation/index.html

12 See http://electrification.energydata.info

datasets used to carry out the electrification planning, such as demographic, resource and infrastructure data publicly available[13].

The methodologies of this research work have been reviewed by international energy experts in relevant international organizations and companies, such as the World Bank, the International Energy Agency, United Nations Department of Economic and Social Affairs and ABB. Some of the findings of this work have been discussed in a side event at the 2015 Paris Climate Conference (COP21). Also, results from this thesis work have been presented at the seminar "How GIS is changing the way we do access?" organized by the World Bank group, where leading researchers in the field participated. This work has also featured in several international workshops and conferences. Such are the General Assembly of European Geosciences Union (2016 and 2017), the NASA-ESA International Workshop on Environment and Alternative Energy (2013 and 2015), the workshop on "Earth Observations and the Water-Energy-Food Nexus" (2013), jointly organized by the Food and Agriculture Organization of the United Nations (FAO), the European Space Agency (ESA) and the Global Water Systems Project (GWSP).

In addition, OnSSET has been used in academic analysis for several developing countries; main tool used in about 15 MSc and BSc theses and in the course "Energy System Economics, Modelling and Indicators for Sustainable Energy Development" given by KTH Division of Energy Systems Analysis.

Finally, the work presented in this thesis was used to support capacity building activities. In November 2015, several analysts from the Ethiopian Ministry of Water, Irrigation and Energy were trained at the Royal Institute of Technology on how to use OnSSET. Similarly, in August 2016, in Ethiopia, UNDESA in partnership with UNDP and KTH launched a training course aimed at strengthening the science-policy interface to inform sustainable development strategies (141). This course has also been presented at UN's headquarters in New York in December 2016. During this course, high level government officials, development practitioners and UN staff were introduced to electrification planning using geographic information systems and were trained in using OnSSET for electricity access

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13 More information about the developed tool can be found at the following websites:

- OnSSET main website

www.onsset.org

- Open energy system models Wikipedia site

https://en.wikipedia.org/wiki/Open_energy_system_models#OnSSET

- Open source and open data in energy modelling website

https://wiki.openmod-initiative.org/wiki/OnSSET exercises in developing countries. Also, in February 2017, in New Delhi, India and in collaboration with World Bank energy specialists, OnSSET was introduced to experts from various institutions of the government of Afghanistan in order to help with their national energy access planning efforts. OnSSET (142) has been adopted as part of the Open Tools, Integrated Modelling and Upskilling for Sustainable-Development OpTIMUS community of practice, of the UNDESA, UNDP, World Bank Group and others (143).

Synopsizing, the methodologies developed in this thesis can be used or further enhanced by: the private sector in order to identify market opportunities; governments, in order to explore the potential role renewable energy sources and off-grid solutions could play in energy access strategies; and academia to enhance and apply further the suggested toolkits and help address energy access issues.

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