Environmental Life Cycle Assessment of Ethiopian Electricity Generation Systems: A Case of Hydro and Wind Power

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A thesis submitted to

The School of Chemical and Bio Engineering

Addis Ababa Institute of Technology

Addis Ababa University

Presented in Fulfillment of the Requirement for the Degree of Doctor of Philosophy

(Chemical Engineering specialized in Environmental Engineering)

Addis Ababa, Ethiopia

November 2020

Addis Ababa University

School of Graduate studies

This is to certify that the thesis prepared by belay Teffera entitled: *Environmental Life Cycle Assessment of Ethiopian Electricity Generation Systems – A Case of Hydro and Wind Power* and submitted in fulfillment of the requirements for the Degree of Doctor of philosophy (Chemical Engineering specialized in Environmental Engineering) complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

Signed by the Examining committee

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Dedicated To

My father Teffera Yalew and

My mother Tagegne Tsegaye

who have passed way during this study

Abstract

Electricity is one of the most vital elements in modern society. Despite its significance to improve human life, there are concerns on its environmental impacts. Life Cycle Assessment (LCA) is a well-established tool for assessing the environmental burdens of products (goods and services) throughout their life cycles. Several LCA studies were conducted for electricity generation and supply systems. However, the LCA data of electricity systems are country specific in their nature. In addition, existing LCA and inventory modeling efforts are limited to the circumstances of the developed world. Therefore, the need to evaluate the environmental performance and to develop country specific LCA data that describe actual electricity systems remains important.

This thesis provides a picture of current electricity system and presents for the first time the LCA results of hydro and wind power systems in Ethiopia. The assessment aims to model existing hydro and wind energy systems and develop LCI and LCA datasets of the country per 1 kWh electricity generated. For both case studies, process-based attributional LCA has been applied using SimaPro software version 8.0.1 and ReCiPe 2008 as impact assessment method.

The main midpoint environmental impacts of Ethiopian hydropower system consisting of eleven hydropower plants operational in 2013-2017 were: climate change(CC): 32 g CO_2 eq., fossil depletion (FD): 0.82 g oil eq., freshwater eutrophication (FWEU): 0.000132 g P eq., human toxicity (HT): 0.58 g 1, 4-DCB eq., metal depletion (MD):1.04 kg Fe eq., marine ecotoxicity (MET): 0.01 kg 1,4-DCB eq., natural land transformation (NLT): 8.3E-04 m^2 eq., particulate matter formation (POF): 0.15 g PM10 eq., photochemical oxidant formation (POF): 0.03 g NMVOC eq., terrestrial acidification (TA):

0.02 g SO_2 eq. and freshwater ecotoxicity (FWET): 0.005 g 1,4-DCB eq. per 1kWh electricity generated.

The major midpoint environmental impacts of Ethiopian wind farms composed of 3 wind farms operational in 2015-2017 were: climate change (CC):33.36 g CO_2 eq., fossil depletion (FD): 8 g oil eq., freshwater ecotoxicity (FWET): 0.023 g 1,4-DCB eq., freshwater eutrophication (FWEU): 0.005 g N eq., human toxicity (HT): 9.9 g 1,4-DCB eq., metal depletion (MD): 18.7 g Fe eq., marine ecotoxicity (MET):0.098 g 1,4-DCB eq., particulate matter formation (PMF): 0.097 g PM10 eq., photochemical oxidant formation (POF): 0.144 g NMVOC eq., terrestrial acidification (TA): 0.21 g SO_2 eq. and natural land transformation (NLT): 1.4E-06 m^2 eq. per 1 kWh electricity generated. The cumulative energy demand and the energy return on investment (EROI) are 0.393 MJ/kWh and 9.2 respectively.

The contribution analysis shows that the pre-operation phase of hydropower plants contributes the highest share (62-99%) in most impact indicators, with the exception that the operation and maintenance phase accounts for about 50 and 90% share in POF and CC respectively. Moreover, medium-scale hydropower plants have higher potential environmental impacts when compared to large-scale hydropower plants. Similarly, the pre-operation phase of wind power is the largest contributor to all the environmental impacts, with the shares ranging between 82 and 96%. In addition, the sensitivity and scenario analyses indicate that the changes in lifespans, exchange rates for parts, capacity factors, transport routes and treatment activities would result in significant changes in the LCA results

The results of the assessment show that the lifecycle of wind power generation has more impacts in most impact categories than hydropower generation, except particulate matter formation (PMF), natural land transformation (NLT) and water depletion. In many cases, a single impact category is caused by many processes associated with few lifecycle stages. This demands the engagement of many stakeholders including academia, researchers, developers, operators and policy and decision-makers.

In general, these studies would give insight for operators and developers to pay proper attention on determination of sites, capacities and lifespans of power plants and end-of-life waste management options. More importantly, this study can serve as an input to a comprehensive life cycle assessment database of the national energy system in Ethiopia, which is in turn vital to develop communication metrics such as Environmental Product Declarations (EPDs) for economically significant export products in Ethiopia, including electricity itself. However, the results of this study should be interpreted within the context of the data limitations encountered during the course of the research, namely, lack of local datasets for electricity, transport and waste treatment activities relevant to local conditions. Future efforts in Ethiopia should, therefore, be dedicated to undertaking the creation of life cycle inventory databases with a focus on such background systems that will serve as a backbone for all kinds of LCAs in the country, and in and beyond the Horn of Africa region at large.

Acknowledgment

During my study period, I have the opportunities of working with several peoples to whom I would like to express my thanks.

I would like to extend my sincere gratitude to my advisor, Dr. Berhanu Assefa, Associate Professor at the school of Chemical and Bio Engineering, Addis Ababa Institute of Technology (AAiT), for his supervision and guidance. I thank him for his encouragement and guidance from inception to the end of the study.

I owe a large debt of gratitude to my co-advisor, Dr. Getachew Assefa, Associate Professor at School of Architecture, Planning and Landscape, University of Calgary, Canada. I want to extend my special thanks to him for providing me with SimaPro software and consistent support in the life cycle analysis.

My thanks go also to Professor Anna Björklund for hosting my research visit at Division of Environmental Strategies Research, Department of Sustainable Development, Environmental Science and Engineering, KTH Royal Institute of Technology, Sweden.

I am also highly indebted with staffs of School of Chemical and Bio Engineering at Addis Ababa Institute of Technology (AAiT) of Addis Ababa University in particular, and Addis Ababa University (AAU) in general for all those direct and indirect supports you provided me during my study. This study has not been possible without the scholarship awarded to me by Bahir Dar Institute of Technology (BiT) of Bahir Dar University for the PhD scholarship. Thus, I would like to extend my best thanks to BiT/BDU. I need also thank experts of Ethiopian Electric Power (EEP) and Ethiopian Electricity Utility (EEU) for sharing their experience and knowledge generously.

I express my genuine thanks to Mr. Tafere Addis, Mr. Sendeku Tekele, Dr. Belachew Getnet and Mr. Zelalem Adane for your enduring support and encouragement throughout my study. I convey my deepest thanks to my family members, Gashu, Belay, Jone, Nigus, Tadesse and all my brothers and sisters for your support and togetherness in my hard times.

Finally, my sweetest thanks to my wife Mrs. Meseret Zewdu and my children Helina, Kidus, Yohannes and Absalat; none of this would have been completed without their moral support and inspiration.

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Acronyms

aCLA	Attributional Life Cycle Assessment
ASWF	Ashegoda wind farm
AWF I	Adama I wind farm
AWF II	Adama II wind farm
BOM	Bill of Material
CC	Climate Change
CF	Capacity Factor
CH_4	Methane
cLCA	Consequential Life Cycle Assessment
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2 eq.	Carbon dioxide equivalent
CRGE	Climate Resilient Green Economy
DDPMG	Direct drive permanent magnet generator
EA	Environmental Assessment
EC-JRC	European commission, Joint research center
EEP	Ethiopian Electricity Power
EEU	Ethiopian Electricity Utility
EIA	Environmental Impact Assessment
EIOA	Extended input output Analysis
EPA	Environmental Protection Agency
EPD	Environmental Product Declaration
ERA	Environmental Risk Assessment
EROI	Investment Return on Investment
FD	Fossil Depletion
FWEU	Freshwater Eutrophication
FWET	Freshwater Ecotoxicity
GHG	Greenhouse gas
GTP	Growth and Transformation Plan
GWP	Global Warming Potential
HAWT	Horizontal axis wind turbine
HPP	Hydropower plants
HT	Human Toxicity
ICS	Interconnected system
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IHA	International Hydropower Association

IO	Input-output
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventories
LCIA	Life Cycle Impact Assessment
LCT	Life Cycle Thinking
LHP	Large hydropower plant
MD	Metal Depletion
MFA	Material Flow Analysis
MHP	Medium hydropower plant
MoFED	Ministry of Finance and Economic Development
MoWE	Ministry of Water and Energy
NLT	Natural Land Transformation
O&M	Operation and maintenance
pLCA	Process-based Life Cycle Assessment
PMF	Particulate Matter Formation
POF	Photochemical Oxidant Formation
RoR	Run-of-River
SCS	Self-Contained System
SEA	Strategic Environmental Assessment
SFA	Substance Flow Analysis
SHP	Small hydropower plant
TA	Terrestrial Acidification
UNDP	United Nations Development Program
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
VAWT	Vertical axis wind turbine

List of publications

This Doctoral Thesis is based on the work presented in the following appended publications

I. Teffera, B., Assefa, B., Björklund, A., & Assefa, G. (2020) Life cycle assessment of wind farms in Ethiopia. *The International Journal of Life Cycle Assessment*. DOI: 10.1007/s11367-020-01834-5. **Impact factor 4.842**

II. Teffera, B., Assefa, B., & Assefa, G. (2020). Assessing the life cycle environmental impacts of hydroelectric generation in Ethiopia. *Sustainable Energy Technologies and Assessments.* https://doi.org/10.1016/j.seta.2020.100795. **Impact factor 3.427**

III. Teffera, B., Assefa, B., & Assefa, G. (2020. A comparative life cycle assessment of hydro and wind power system with Ethiopian case studies. Manuscript for *Renewable Energy. Under prepartion*

1. INTRODUCTION

This chapter presents the introduction of the study. It begins by explaining the interplay between electricity generation and the environment and giving a short overview of the Ethiopian electricity system. Next, it discusses on widely employed assessment tools and why the life cycle assessment (LCA) methodology was selected. Then, it states the motivation of the research followed by the aims, scope and significance of the study. Finally, the chapter outlines the structure of the thesis.

1.1. Electricity generation and the environment

Electricity is one of the most important elements for socio-economic development and improving quality of human life. In modern society, be it luxury or basic, social and economic activities are dependent on supplies of electricity. Aside from powering devices in our homes, electricity can be used to build and run factories and lighting our cities. Several studies show that economic growth and social-being have strong relationship with electricity consumption (Yoo, 2005; Shahbaz et al., 2011; Awad and Yossof, 2016; Ram et al., 2020). According to the International Energy Agency (IEA, 2020), the world average electricity generation and consumption were increased from 5,094 TWh in 1973 to 22,303 TWh in 2018 respectively, with an increase more than 7.5 % per year .

Despite its significance in economic growth and improving standard of human life, there is a consensus that there exists no energy source which is free from environmental impacts (IAEA, 1999). In addition to resource consumption, electricity generation is the main sources of CO_2 emissions accounting for about 40% followed by transportation (31%) and industry (14%) (Abdallah and El-Shennawy, 2013). The total world CO_2 emissions associated to energy from fuel combustion has increased from 15.5 gigatonnes in 1973 to 33.5 gigatonnes CO_2 in 2018, which is more than 116% increment (IEA, 2020). In the same year, the energy sector contributed about 89 % of total global CO_2 and GHG emissions (i.e., about 37.5 Gt CO_2 and 55.6 Gt GHG emissions) (EC-JRC, 2019; UNEP, 2019; Olivier and Peters, 2020). Therefore, combating climate change through use of low-carbon energy system has become at the heart of energy policies of many countries (EC-JRC, 2018). Although its contribution to global GHG is low (about 0.04%), the government of Ethiopia has developed energy policies and strategies that guide electricity generation from renewable energy sources to reduce the net GHGs emissions.

1.2. Ethiopian electricity system - Overview

Ethiopia is an ancient independent country located in the Horn of Africa between 3^o and 15^o N and 33^o and 48^o E; with a total area of about 1,100,000 km^2. Ethiopia endowed with different climate zones varying from hot, semiarid lowlands to cool, humid highlands, where there are two distinct seasons: the rainy seasons June to September and the long dry seasons October to May (Steeneveld GJ, 2014; Fazzini et al., 2015; Asefa et al., 2020). According to World Bank, with the population of about 112 million people in 2019, Ethiopia has registered 9.9 % an average an average annual growth during 2007/2008-2017/2018, which is the fastest economic growth compared to a regional average of 5.4% (World Bank 2020). The government of Ethiopia has envisioned to transform the country to a lower middle-income status by 2025 (MoFED, 2010).

Modern electricity generation in Ethiopia has been started in early 1940s with the development of Aba Samuel hydropower pant (World Bank, 1964). Ethiopia owns excellent renewable energy resources. These include hydro, wind, geothermal, solar and biomass.

Hydroelectric power is the most important renewable energy source in Ethiopia owing to the availability of large water resources. The hydro, wind and geothermal potentials are estimated about 45, 1350 (i.e., at wind speed > 6.5m/s) and 7 GW per year respectively and an average solar power potential of about 5.2 KWh/m^2 per day (Tucho et al. 2014; Azeb, 2015).

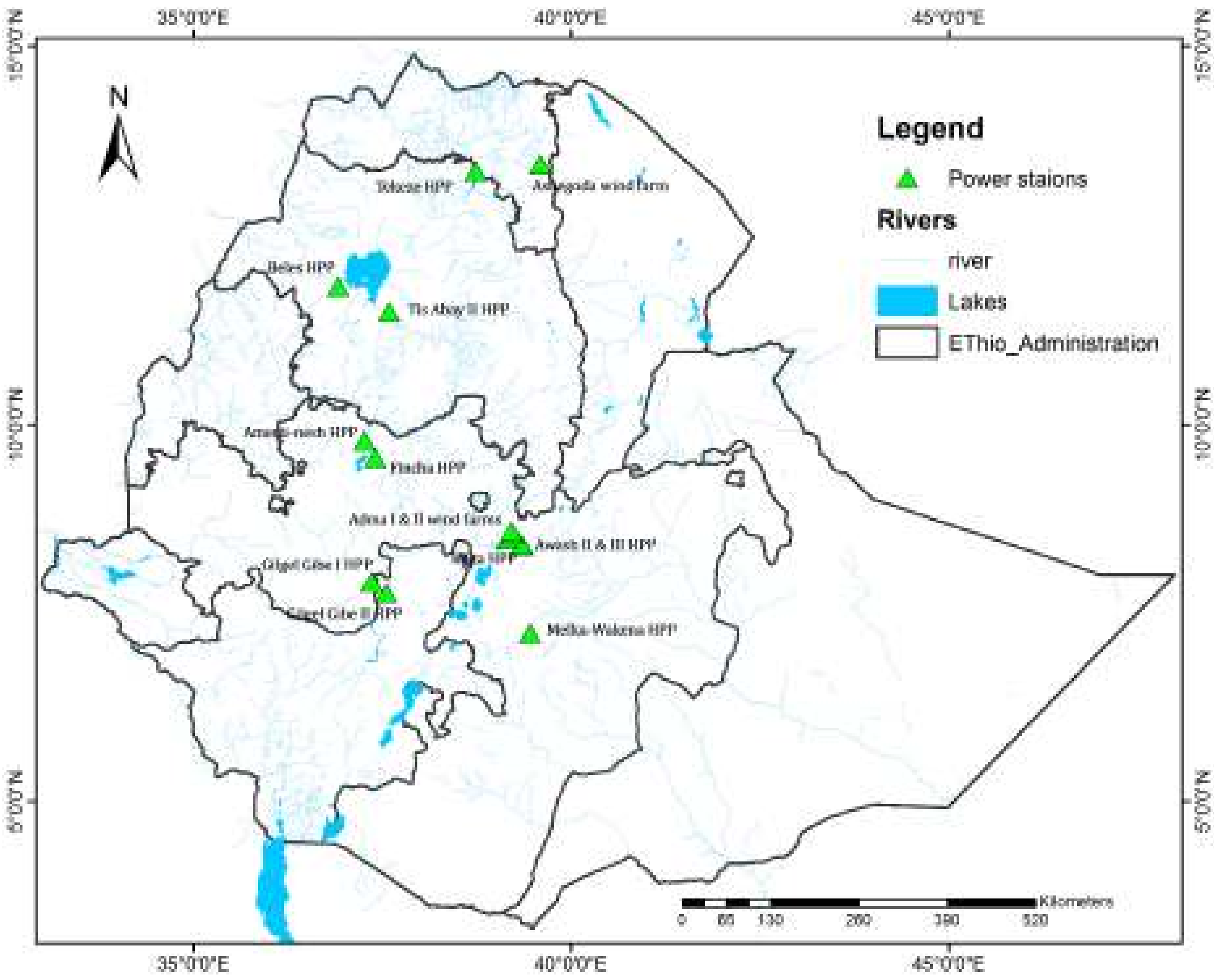


Figure 1.1 Map showing locations of main hydro and wind power plants in Ethiopia.

Adam I and Adam II wind farms are two sperate wind farms, but near to each other. Similarly, Awash II and Awash III hydro powers are distinct, but separated in few kilometers. Regarding installed capacities: Amerti Neshi HPP (97 MW), Beles HPP (460 MW), Gilgel Gibe II HPP (420 MW), Tekeze HPP (300 MW), Gilgel Gibe I HPP (184 MW), Tis Abay II HPP (73 MW), Malka Wakana HPP (153 MW), Fincha HPP (134 MW), Awash III HPP (32 MW), Awash II HPP (32 MW), Koka (Awash I) HPP (43 MW), Adama I wind farm (51 MW), Ashegoda wind farm (120 MW), Adam II wind farm (153 MW). *(Source*. Ethiopia Electric power (EEP) information desk)

According to United States energy information Agency (2019), in 2018 the total installed capacity of electricity generation in Ethiopia was about 4.4 GW, in which about 107% increase against 2010; hydro, wind, biomass and waste, thermal and geothermal energy sources cover about 87.7%, 7.4%, 4.4%, 2.3% and 0.2 % of the total. The electricity consumption in Ethiopia has increased from 3,837 GWh in 2010 to 10,224 GWh in 2018; which is an increase of about 18.5 % annually (IEA, 2020). Currently, the electricity generation system in Ethiopia consists of hydropower plants, wind farms, geothermal, thermal plants and small solar units connected into either the into-connected systems (ISC) or self-contained system (SCS). The national ICS is currently relay on electricity generated from hydropower and wind power, accounting about 92 and 8% respectively (IHA 2019). The SCS system is connected to few small hydropower plants, thermal plants and small solar systems. The National Electrification Program, launched in 2017, outlines a plan to reach 100 % access by 2025, where ICS and SCS will cover 65 and 35 % of the population respectively (FDRE, 2019). **Figure 1.1** above depicts a map showing the locations of hydro and wind power plants covered in this research.

The national energy policy envisioned to make Ethiopia 'a regional hub of renewable energy' by developing its hydro, wind, solar, geothermal and bio-energy resources (MoWE, 2012b). In its green development strategy, which is called Climate-Resilient Green Economy (CREG) strategy, the government identifies renewable energy development as the most practical option to build green economy (FDRE, 2011a). According to CREG, alternative or renewable energy sources are not seen or taken as just alternative energy sources for the country, or an option, but it is the main energy sources. In addition, the development of renewable energy for domestic and regional markets remains the strategic directions of the two consecutive Growth and Transformation Plans (GTP I and GTP II), which have been prepared and implemented to achieve country's vision to medium incomes status (MoFED, 2010; NPC, 2016). The green growth strategy assumes that renewable energy development can help to limit the GHG emissions of electric power sector at level of 3Mt CO_2 equivalent; although method of assessment is not explicitly provided.

However, studies show that even renewable electricity technologies/systems present detrimental environmental impacts (IAEA, 1999; Markandya and Wilkinson, 2007; Bozkurt, 2010). The environmental impacts of electricity generation are diverse, besides the CO_2 or GHG emissions, even renewable electricity sources consume natural resources and generate wastes with potential harm to human health and the environment (IAEA, 1999; Markandya and Wilkinson, 2007; Bozkurt, 2010). In addition, the environmental impacts of electricity generation systems are diverse and GHG emissions could not be used as the only indicator to represent the environmental performance of electricity systems. Besides GHG emissions, environmental impacts of electricity generation include the consumption of resources and emissions resulting in natural resource deletions, acidification, eutrophication and ecological toxicities. Therefore, in order to better understand their environmental performance and to make informed environmental decisions, the assessment of electricity generation systems for various environmental indicators is important from a life cycle perspective.

1.3. Assessment tools and Applications

There are several environmental assessment tools including Material Flow Analysis (MFA) (e.g., bulk material flow analysis and substance flow analysis), Environmental Impact Assessment (EIA), Strategic Environmental Assessment (SEA), Environmental Risk

Assessment (ERA), life cycle assessment (LCA) and others (Haes et al., 2000; Finnveden and Moberg, 2005). Based on the principle of mass balance, MFA tools are used to analyze material and substance flows between the environment and the economy in certain region at given time period (Bao et al., 2010; Huang et al., 2012). They are mainly for the quantifications of material flows in physical units (e.g., in killograms) and do not explicitly include environmental assessment (Bao et al., 2010). The ERA is used to evaluate the health and environmental risks of substances, projects and policies at specific space and time. While all EIA, SEA and LCA consider natural resource consumption and environmental impacts, their study objects and boundaries in terms of space and time are different. The EIA is used to evaluate environmental impacts of projects, whereas SEA tries to predict impacts of policies, projects and substances (Cole and Broderick, 2007; Morrison-Saunders and Fischer, 2006). LCA studies input and output flows and associated impacts of a product system throughout its life cycles (ISO, 2006a, 2006b), often independent of space and time (i.e., processes can possibly be in a different places and at different times).

These classifications of environemnetal assessment tools are not sharp and rigid that they are changing with time. For instance, tools such as EIA and SEA often use other analytical tools like LCA and ERA (Manuilova et al., 2009; Larrey-Lassalle et al., 2017), EIA is used to supplement LCA (Morero et al., 2015) and MFA provides material inventories data for LCA (Turner et al., 2016). There are also growing interests towards dyanamic LCA analysis that considers changes in space and time (Maier, 2017) and sustaiability assessment (Kloepffer, 2008; Simões et al., 2013; Zamagni et al., 2013), in which LCA also examines socio-economic impacts of products. The LCA technique based on the concept of life cycle thinking has shifted the project and site-specific production impact assessment to a holistic product impact assessment. LCA thus enables to bring all flows and impacts attributed to a product into one system model, irrespective of where they occur, and to avoid the transfer of emissions and impacts to different life cycle stages, locations or different components of the environment. This holistic approach underlying LCA helps for assessing potential global environment impacts such as climate change (Grösser et al., 2017).

Life cycle assessment (LCA) has been widely used to assess electricity generation systems and the results (LCI/LCA data) of electricity have many applications. Besides to better understanding the environmental performance of electricity generation system through identification of 'hotspots' that support operational improvement, LCA data are used for comparing electricity technologies (e.g., WNA, 2011; Jin Zhang et al., 2015;Wanga et al., 2019) that aids for strategic planning; developing performance metrics like Environmental Product Declaration (EPD) of the electricity systems (EDF Energy, 2009; Gamesa, 2015; Vattenfall-AB, 2013a, 2013b)(Vattenfall-AB, 2013b). The EPD, also known as Type III environmental declaration, is a verified environmental document of goods and services prepared in line with the international standard ISO 14025 (Del Borghi, 2013), which provides reliable environmental information to stakeholders and consumers (i.e., backing communication and marketing decisions). The LCI data of electricity is also useful to perform LCA studies of other products for electricity is an important input in almost all products (i.e., supporting in product and process development).

1.4. Motivations for the thesis

According to Kothari (2004) and Shmatko and Volkova (2017) , the motivations for given research can range from personal career development to the need to contribute in the field as well as in the area of study. Personally, it was my interest to evaluate the nexus between the energy and environment from a systemic perspective and to generate environmental information for real background systems such as electricity. This is because the environmental data of such systems can have critical roles in other sectors too. Therefore, although there are many LCA studies of electricity systems in the literature (Asdrubali et al., 2015b), there are still significant reasons that motivate me for this study in the sector.

First, the electricity LCA data of each country are unique due to difference in geography, energy technologies and lifetime of production processes (Suksuntornsiri and Limmeechokchai, 2005). In addition, according to World Energy Council (WEC, 2004), the inconsistencies in methodological choices and assumptions during LCA studies highly affect comparison between similar or different electricity technologies. Moreover, existing studies are limited to conditions of developed countries (Turconi et al., 2013a), which means the application of LCA for electricity sector would continue as there is a need to technology and geography-specific and harmonized LCI and LCA data for electricity technologies/systems.

Second, to the best knowledge of this writer, there is no literature providing an overall environmental analysis of Ethiopian energy sector in general, electricity in particular from life cycle perspective. Previous studies concentrated on energy supply and demand, energy resources potentials, feasibility studies and energy development policy options. For instance, Mulugetta (1999) reviewed rural energy use in terms of energy supply patterns and consumption tends, Wolde-Ghiorgis (2002) reviewed the energy sector and recommended policy options for rural energy development, Tucho et al. (2014) assessed the contribution of renewable energy sources, Diriba and Börner (2015) investigated the optimal least cost of energy sources, Mondal et al. (2017, 2018) modeled long-term energy supply and demand scenarios respectively, and Mulugetta (2007) reviewed the potentials for expanding renewable sources in Ethiopia. There are also many feasibility studies related to specific energy sources. For instance, the solar power potential in Ethiopia was evaluated by (Bekele, 2011) and Mahmud et al. (2014); hydropower potential by Girma (2015), Mulugeta et al. (2015) and Nigussie et al. (2017); wind power potentials by Asress et al. (2013); geothermal potentials by Bahati (2011) and Kebede (2012) and biomass potential by Geissler et al. (2013). Hence, existing few LCA studies conducted for Ethiopian products either did not consider LCI data for electricity (Bekele, 2007) or use proxy LCI data developed for different energy mixes (Sahle and Potting, 2013) for assessing the life cycle environmental impacts of Glove Leather production and rose production in Ethiopia respectively.

Third, the Ethiopian electricity generation and transmission system is massively expanding from a miniscule couple of hundreds of megawatts to over ten thousand megawatts in the coming few years. The development dominated by expanding the existing hydropower capacity is expected to maintain the economic growth of the country of over 110 million people. Currently, Ethiopia is building the Africa's largest hydroelectric plant which as an installed capacity of 6000MW both to ever growing domestic demand and export to neighboring countries. The Ethiopia's grid is getting importance not only as the grid of the most populous countries in Africa but also a power hub that will affect the region as it continues to export to other countries. Ethiopia is already exporting electricity to neighboring countries such as Sudan, and Djibouti and is envisioned to supply to other countries in region such as Kenya and Egypt and thus the modeling of the Ethiopian electric system is also regionally significant

Therefore, the motivation for this thesis is to contribute for the creation and availability of country specific (as yet regionally significant) LCI and LCA data of Ethiopian electricity system, which can present valuable information to academics, LCA practitioners, the developer and operators in the industry.

1.5. Statement of the problem

Given the wide-ranging of concerns over its environmental burdens and critical significance on environmental performance of other product systems, the creation and availability of quality environmental information of electricity system is necessary. This needs the evaluation of environmental impacts associated with electricity systems using environmental assessment tools to support sound environmental decisions in the sector.

As presented in section 1.3, the LCA tool has been widely applied for assessing the environmental impacts of electricity generation systems from a holistic perspective using the concept of life cycle thinking that enables to identify and evaluate all impacts within one framework. Unfortunately, LCA studies of energy systems are country-specific in their nature, existing LCA studies are limited to situations of developed countries and inconsistent in approaches. More importantly, the environmental performance of the Ethiopian electricity system is not yet studied from a holistic manner although its regional significance is increasingly growing. Therefore, this thesis is dedicated to evaluating the life cycle environmental impacts of the electricity generation system in Ethiopia, hydro and wind power systems are the case studies. The reason for the selection of hydro and wind power systems is mainly attributed to their significant contribution in current and future energy system of Ethiopia.

1.6. Aim and objectives of the thesis

The overall aim of this study is to contribute to the creation of LCA database on electricity generation systems in Ethiopia using life cycle assessment methodology. The main objective of thesis is to estimate the cradle-to-grave life cycle environmental impacts associated with hydro and wind power systems supplying high voltage electricity to the national grid. To achieve the aim and objective of the thesis, the research work will address the following specific objectives:

- Evaluate the life cycle environmental impacts of hydropower systems
- Evaluate life cycle environmental impacts of wind power systems
- Synthesize key LCA results of hydro and wind power systems

The contribution and sensitivity analyses were conducted for each electricity technology in order to identify dominant sources of impacts and assess the implications of changes in parameters and assumptions on the overall impacts, respectively.

1.7. Scope of the thesis

The scope of this thesis work involves data collection, system modeling, data analysis, contribution and sensitivity analyses and synthesis of key results. It mainly covers processes and impacts of electricity generation systems connected to the central or Inter-Connected System (ICS). According to the information from Ethiopian Electric Power (EEU) and (IHA 2019), in 2017, the ICS was entirely dependent on electricity generated from hydro and wind power systems, accounting about 92 and 8% respectively. The small power plants connected to off-grid or Self-Contained System (SCS) are not considered.

1.8. Research questions

This study is about the evaluation of the life cycle environmental impact of electricity generations focusing on hydro and wind power systems. It tries to answer the following research questions:

- What are the significant environmental impacts of hydro and wind power systems?
- What is the dominant life cycle phase in each electricity generation system in terms of contribution to life cycle environmental impact?
- To what extent do changes to key parameters such as lifespan, energy production data, recycling rates, transportation distance and replacement rates influence the outputs of each model?
- Which electricity generation source performs environmentally better: hydro or wind power?

1.9. Significance of the study

As Ethiopian power system is becoming regionally significant by supplying electricity to neighboring countries, system-wide information on the power system is vital. The overall contribution of this thesis is the provision of LCA dataset for the most important electricity sources in Ethiopia, hydro and wind power systems that represent almost 100% of current electricity generation system in Ethiopia. The resulting LCA data is important as such to compare alternative electricity generation technologies/sources in terms of their environmental performance and to make informed choices among them. More importantly, it can help as an input to a comprehensive life cycle assessment database of the national energy system in Ethiopia.

In addition, as the first attempt to apply LCA for large real system in Ethiopian context, and electricity is an important component of almost all product systems, the results can serve to perform LCA studies for nationally significant export products like coffee, leather and flowers based on actual primary data, instead of assumption and proxy data for electricity. Hence, the life cycle environmental performance of electricity sources would have significant implications in local industries and be useful in making the right investment decisions in a climate constrained economy of the near future. Therefore, this thesis and its findings are expected to offer useful information for academics, LCA practitioners, decision-and policy-makers including developers and operators related to energy technologies in Ethiopia.

1.10. Structure of the thesis

Excluding the introduction part, the thesis is divided into six chapters. Chapter 2 begins by discussing about environment decisions, environmental assessment tools and life cycle thinking. Then, it presents a detail overview of the principles, framework and concepts of LCA, LCA software and databases, and compilation and computational structures. Next, it provides a review of previous LCA of electricity systems, mainly for hydropower and wind power followed by a brief discussion on the potential applications of LCA results. Last, it gives a short summary of chapter 2 and highlights about general approaches and assumptions to be used in following chapters. Chapter 3 and 4 develop full real LCA case studies for existing Ethiopian hydro and wind power systems, respectively. Chapter 5 synthesizes the key results in Chapter 3 and 4. Finally, chapter 6 presents the conclusion, limitations and policy recommendations of the study.

2. LITERATURE REVIEW

This chapter offers the literature review of the study. Initially, it explains the need to incorporate the environment into decisions and describes the process and methods for the generation of environmental information. Next, it examines the main steps of LCA methodology and supporting LCA software and databases. Then, it gives a systematic review on existing LCA studies on energy technologies, in particular the hydro and wind power systems. This is followed by a discussion on application of LCA studies and their results. At last, the chapter summarizes the limitations of reviewed studies and provides general methodological approaches and key assumption that are applied in the proceeding case studies at chapter 3 and 4.

2.1. Decisions for the environment

2.1.1. Processes in environmental decisions

At any single moment, environmental decisions are being made. For instance, a homeowner decides whether to buy a gas or electrical cooker; a developer decides whether to invest on small- or large-scale hydropower schemes; a government decides to increase wind power in the electricity mix against hydropower schemes, etc. Each of these actions has environmental effects that reach far beyond the person or group making the decisions. According to Scion and Scion (2007), any decision making process involves definition of the problem, identification of possible alternatives, evaluation of alternatives and making the decision. In particular, Sexton et al. (1999) define environmental decisions as "choices that individuals, groups, organizations and societies make about the environment or affecting the environment". Therefore, environmental decision making is a process of evaluating the environmental impacts of different alternatives and selecting the alternative(s) with lowest adverse impacts.

2.1.2. Methods and tools

Informed decisions need reliable information about the environmental implications of the decisions by consumers, producers and policy makers. This in turn requires collection objective, accurate and comprehensive information and evaluate the significance of these impacts. Environmental Assessment (EA) is a process of an 'objective evaluation and analysis of environmental impacts' of operating or intended development activities to support planning and decision-making (UNEP, 2015), while environmental management is the management of those activities with significant impacts on the environment (Starkey, 1998; UNDP, 2011). EA has been an integral part of environmental management since 1972, following the UN Conference on the Human Environment in Stockholm (DuBose et al., 1995). In his book review work, Lee (2020) summarized that environmental assessment provides two types of environmental information for decision-makers: one is the environmental information they require for actual decisions and the other is the environmental information that introduce them on the values of environmental management. Therefore, using different tools and techniques, EA is used to collect and evaluate environmental information relevant to decision-makers.

EA applies several tools and methods to gather and evaluate information. These assessment and management tools include Material Flow Analysis (MFA) and Substance Flow Analysis (SFA), Environmental Impact Assessment (EIA), Strategic Environmental Assessment (SEA), Environmental Risk Assessment (ERA), life cycle assessment (LCA), Environmental Management System (EMS), Environmental Audit, Environmental

Monitoring and others (Haes et al., 2000; Finnveden and Moberg, 2005). These tools have different aspects in terms of their object of study, space and time consideration, and system modelling approaches.

Haes et al., (2000) divide these tools in two groups: analytical and procedural tools. They suggested that analytical tools consist of mathematical models (e.g., LCA, MFA and SFA), where as procedural tools such as EIA and SEA use guidelines to control responsibilities and process steps. Finnvedena and Moberg (2005) have further classified assessment tools into four groups based on: whether they are procedural or analytical, types of impacts considered (i.e., natural resource or environment impacts), object of study (i.e., policy actions, project, product, total or single material flow) and types of analysis (i.e., descriptive or prospective). MFA with all its variants considers only physical material flows in certain region at given time period. EIA aims to predict resource use and environmental impacts of projects at specific place and time; ERA aims to predict health and environmental harms derived from policies, projects and substances; LCA examines the same impacts as EIA but at product level. On other hand, descriptive (retrospective or accounting) analysis aims at examining the object of study how it works; whereas prospective (change oriented) analysis aims at examining effects of changes on the object of the study (e.g., technology change). Table 2.1 below summarizes the classification of EA tools.

This classification of EA tools is not sharpe and rigid, rather they are are evolving with time. For instance, tools such as EIA and SEA often use other analytical tools like LCA and ERA (Manuilova et al., 2009; Larrey-Lassalle et al., 2017) and EIA is used to supplement LCA (Morero et al., 2015). There are also growing interests towards dyanamic LCA analysis

Table 2.1 Characteristics of environmental assessment tools

EA Tool	Object of study	Space and time	Type of analysis	Focus
MFA	materials/energy	Region, fixed period (1 year)	Descriptive	NRC
SFA	Substances/products	Region, fixed period (1 year)	Descriptive	NRC
LCA	Products/materials	Neither site nor time- specific	Both	NRC and EIs
EIA	Projects	Both site and time- specific	Prospective	NRC and EIs
SEA	Polices and plans	Both site nor time- specific	Prospective	NRC and EIs
ERA	Polices, substances	Both site nor time- specific	Prospective	EIs

Note: NRC = natural resource consumption and EIs = environmental impacts (including human health)

(Maier, 2017) that LCA considers space and time aspects and LCA also examines socio-economic impacts of products (Kloepffer, 2008; Simões et al., 2013; Zamagni et al., 2013). Although there is no a fast and hard criteria, classfication of EA tools using their characteristics would give insight on what a tool does and what it does not do.

2.2. Life cycle thinking (LCT)

The concept of "life cycle" attaches itself with the advent of Agenda 21 in early 90s. Chapter 4 in agenda 21 calls for governments and international organizations to "develop criteria and methodologies for the assessment of environmental impacts and resource requirements throughout the full life cycle of products and processes"(UN 1992). Life cycle thinking is a guiding concept that requires the accounting of all exchanges between the environment and technical systems (e.g., any product), starting from raw material mining, manufacturing its components until the last end-of-life treatment. It demands the evaluation of implications of a product beyond the traditional focus on production sites including its use and end of life phase (UNEP 2007). Life cycle assessment (LCA) is one of the approaches to implement life cycle thinking. LCA has been a preferred tool to make a shift from project-and site-specific production to a holistic product impact assessment in which the value chain of the product is assessed as a system. Traditionally, LCA is favored for assessing potential global environment impacts (e.g., climate change), which are aggregates of emissions occurring throughout a product system (i.e., possibly at different times and in a different places). The following section and subsections therefore deal with principles, methodological issues and applications (i.e., in energy systems) of LCA.

2.3. Life Cycle Assessment (LCA)

The concept of life cycle inventory analysis had its origin in the 1960s with the need to determine energy and materials requirements of products (Vigon et al., 1993; Finnveden et al., 2009; Guinée et al., 2011). In 1969, the Coca-Cola Company commissioned the first LCA study to estimate wastes during manufacturing and use of brewery packaging products. Soon its application grew to include other environmental information on global warming, acidification, eutrophication and resource depletion, ecological and human toxicities. Finally, the impacts are interpreted for their significance and appropriate conclusions are drawn. The collection of environmental loads, evaluation and interpretation of their impacts and making conclusion are set of processes that form life cycle assessment (LCA) (ibid).

Life Cycle Assessment (LCA) is used as a tool to assess the environmental impacts of a product, material or process system throughout its life cycle; from the extraction of raw materials through production and use phases to waste disposal (Haes et al., 2000; Finnveden et al., 2009). It is a holistic approach based on the assumption that the ”true extent of the environmental burden can only be understood if all steps … of a product or service are accounted in in the final analysis”(Ross and Evans, 2002). This approach or perspective allows LCA goes beyond the production sites of products and reduces the shifting of potential environmental burdens between product's life cycle stages, which inspires producers to move well beyond compliance.

LCA is an important EA tool in environmental management. It has been applied in almost all sectors: process industries (Burgess and Brennan, 2001; Papageorgiou, 2009), manufacturing industries (Haapala et al., 2008; Huntzinger and Eatmon, 2009), supply chain optimization (Papageorgiou, 2009), agriculture (Haas et al., 2000; Nemecek et al., 2011; Ruviaro et al., 2012; Iraldo et al., 2014) waste management (Chen et al., 2010; Cherubini et al., 2009; Feo and Malvano, 2009; Güereca et al., 2006; Song et al., 2013) and marketing (Iraldo et al., 2014). As stated by the International Organization for Standardization (ISO), LCA can be used for product design and development, process optimization, strategic planning and Eco-labeling (ISO, 2006a). When applied starting early in the design process, LCA is used to select a product or a process with less material and energy intensity and low wastes and to develop a long-term product policy that considers future regulations and competitiveness.

2.3.1. LCA framework and standards

The International Organization for Standardization (ISO) has established standard frameworks in the ISO14040 to bring uniformity and enable comparison between results of different LCA studies. According to this framework, LCA has four main stages; namely goal and scope definition, inventory analysis, impact assessment, and interpretation.

2.3.1.1. Goal and scope definition

In this stage of LCA, the goal and scope of the proposed study is defined in terms of the goal (aim and objective), and the intended use and users of final results of the study. Basically, the decision-context (i.e., the situation or level of decisions) defines the intended application and the latter defines the purpose (why the LCA is being conducted) and the content of study. This is to mean that LCA studies are intended to support micro-level decisions that would have different goal and scope than those that support macro-level decisions as well as those planned to give a mere descriptive analysis of analyzed system (EC-JRC, 2010). The goal and scope definition step is critical element of LCA, because it defines many important methodological aspects such as functional unit, modeling approaches, system boundaries, allocation and data requirements.

2.3.1.2. Functional unit

In their article 'Full Mode and Attribution Mode in Environmental Analysis', Haels and his coauthors (Haes et al., 2000)state that '[in LCA] it is not a product which is investigated, but the function delivered by a product system'. Therefore, all processes in the product system, as well as their input-output flows are normalized to this function or functional unit. Functional unit can be defined as a quantified performance of a product system and used as a reference unit in the LCA study (ISO, 2006a). For instance, the function of a wind plant is to generate electricity and its functional unit can be 1MW power or 1kWh of energy". Once defined, the functional unit also serves to facilitate comparison with different studies of the same or similar products.

2.3.1.3. System modelling approaches

LCA models describe sets of processes associated to the product system under study. Depending on the purpose (and thus type of analysis) of LCA study, there are two modeling approaches; namely attributional LCA (aLCA) and consequential LCA (cLCA) modelling approaches. The aLCA considers all processes attributed to the product system, which means as they exist. The aim is to examine the environmental impacts of a product system as it exists or modeled to exist. In this modelling approach, average LCI data are used to produce (average) LCA results with intention to give an answer for the questions like 'how does the product system works?'. On other hand, the cLCA approach considers all processes and material flows, but only those which are directly or indirectly affected by an action (e.g., a decision on change of technology). In this modelling approach, average marginal LCI data are applied to produce (average) marginal LCA results to answer for the questions like 'how does the product system behave for a given change?'. These LCA modelling approaches are discussed in many LCA studies (Earles and Halog, 2011; Lund et al., 2010; Martin et al., 2015; Rehl et al., 2012; Styles et al., 2015; Yang, 2016).

In terms of LCI data compilation, there are process-and input-output (IO)-based LCAs. The process-based LCA (p-LCA) analysis has been traditionally carried out since early 1970s to analyze environmental burdens of products (Fava and Page, 1992; Heijungs, 1994). The p-LCA method is the same as aLCA type, where all processes connected to the product system are considered for the analysis. Physical units (e.g., kg and kWh) are used to express quantities of material and energy flows. It is referred as a bottom-up analysis approach by the fact that a product system is modeled using process-specific information (Lewandowska and Foltynowicz, 2004). Regarding computational framework, p-LCA applies simple mathematical operators or matrix method to compute the total inventory data, but the latter is fast and preferred (Suh and Huppes, 2005). On other hand, the IO-LCA analysis (top-down approach) accounts for all processes in the sector or economy containing analyzed system, including those processes outside the system study. It usually expressed as extended IO-LCA (EIO-LCA) to indicate that the typical input-output (IO) table is extended by including environmental interventions proportional to the amount of output of the processes. The IO table, expressed in monetary unit, describes how processes or industries are inter-related though producing and consuming intermediate industry outputs (Hendrickson et al., 1998; Lewandowska and Foltynowicz, 2004; Suh and Huppes, 2005).

In principle, all processes are directly or indirectly connected with each other, but it is unpractical to collect all process-specific data for the whole economy. Therefore, truncation or cut-off some processes is often unavoidable in p-LCA. Process cut-off can be conceived as the exclusion of unit processes from the product system because they are unimportant or because the data are not available (Heijungs and Suh, 2002). On other hand, although it lacks process specificity, EIO-LCA is generally more complete than that of process analysis, but data intensive and environmental intervention data are usually unavailable (Joshi, 1999; Matthews and Small, 2001; De Udo Haes et al., 2004; Lindner et al., 2013). Therefore, one can observe that several combinations can be considered between two modelling approaches and two computational methods depending on the goal of LCA study and availability of data for the study.

2.3.1.4. System boundaries

System boundaries include other systems, space, time and technologies. Defining system boundaries involves the delimitation of a system of focus from other systems (natural or technical) or specifying its processes in terms of space, time and technologies. For instance, a product system and the environment are integrated through material flows from the environment to product system or vice versa. Therefore defining the boundaries between the product system and the environment means identifying these flows and processes (ISO, 2006a). On other hand, inventories of a process may vary from place to place, time to time and as technologies changes. Therefore, it is important to specify the space, time and technology of processes of study system to ensure the validity of the final result.

As discussed above, aLCA and cLCA models would have different system boundaries. An aLCI approach considers all processes and material flows used in the system, whereas cLCA model considers all processes and material flows, but which are directly or indirectly affected by the induced change. In both cases, process-omission or cut-off is applied if they are insignificant or unavailable (Suh and Huppes, 2005; Bellon-Maurel et al., 2013), but rationale should be explicitly documented (ISO, 2006c). The ISO LCA standard recommends up to 5% cut-off for mass and energy and 1% for environmental significance. In addition, the LCA analysis can be full LCA (i.e., cradle-to-grave) if all life cycle stages of system are modeled or partial LCA life cradle-to-gate (e. such as material LCA) and gate-to-grave (e.g., waste LCA) (Haes et al., 2000)

2.3.1.5. Allocation methods

A product or process with more than one function is referred as multifunctional product or processes. For instance, thermal power plant may produce both electricity and heat. If the goal is to examine one of the functions, splitting of flows among the functions is important. The process is called allocation of flows among nonfunctional processes and the steps constitute the allocation procedure. The general allocation procedure is as follow: first when possible avoid allocation through dividing of multifunctional process into its constituent nonfunctional processes or system expansion by including the additional function(s) related to co-products, next split them apparently using physical allocation factors (i.e., using mass and energy unit), finally resort divide them implicitly using economic allocation factors (Heijungs and Suh, 2002).

2.3.1.6. Data requirements

Defining data requirements is used to guide the collection of the right type and quality of data in LCI modeling. Data requirements specify the characteristics of the data that make the data suitable for the study. These include data quality attributes such as representativeness, completeness and precision (EC-JRC, 2010). *Representatives* refer to the ability of the data to represent process regarding to its geography, time and technology of data collection. The LCI data can be specific or average in terms of geographical, temporal or technological coverage of a process it represents. The data can be specific or average in terms of geography, time and technology. *Completeness* describes accuracy of the data when it is checked for basic tools such as stoichiometry, mass and energy balance. On the other hand, the *precision* of the data specifies the gap between the quality of collected or modeled data and the actual process data, i.e., deals with the uncertainty associated with the data. Types of data and information required include inventory information, statistical data, technical process or system information, market information, allocation related information, boundary and legal conditions.

Raw or LCI data can also be *primary* or *secondary* in terms of data sources. Primary data are those collected from activities through direct measurements, patents, processes engineering models, stoichiometric models, process and production specifications and test reports, legal limits, similar processes or best available technologies reference documents. On the other hand, data from literature (articles, reports and other relevant documents) and database are examples of secondary data (EC-JRC, 2010). In terms of subsystems considered, LCI data are also classified as *foreground* and *background* system data. The former refers site and technology specific data from processes which are under the control of the operator of the analyzed system. The background system data are average or generic data for materials, energy, transport and waste management systems in which individual plants and operations are not identified (Zimmermann et al., 1996; US EPA, 2006; JRC-IES, 2010; Kuczenski, 2015)

2.3.2. Inventory analysis

Once all relevant methodological choices are done, environmental burdens (resource use and emissions) inside the defined boundary of the product system are identified and quantified. Therefore, the inventory analysis phase involves process identification, system modeling and then compilation and quantification of unit process inventories (or flows) throughout the product system life stages (ISO, 2006a). The outputs of inventory analysis can be an LCI studies or LCI datasets (EC-JRC, 2010). LCI study results can be used for process analysis, material selection, product evaluation, product comparison and policy-making (Vigon et al., 1993) or converted to environmental impacts in the impact assessment phase (Weidema and Wesnaes, 1997).

2.3.3. Life cycle Impact assessment (LCIA)

The impact assessment phase is used to convert results of inventory analysis into their potential environmental impacts(ISO, 2006). The selection of LCIA method defines impact categories, impact category indicators and characterization models in the LCA analysis (Rosenbaum, 2017). The impact categories refer to the environmental issues covered in the assessment, category indicators are the scores of the impact categories expressed in appropriate substances and characterization models are expression to calculate characterization factors and impact indicators. Once LCI data are assigned into impact categories and or their relative contributions to impact category they are calculated using their respective characterization factors (CFs), which are calculated from the cause-effect chain (environmental mechanisms). Finally, the total impact of the product is computed to each impact category according to LCIA method selected.

Currently, there are two families of impact characterization methods: midpoint and endpoint methods. Midpoint (or problem-oriented) methods focus on environmental problems including climate change or acidification. The endpoint methods show the aggregated impacts on areas of protection due to those environmental problems (UNEP 2003; Jolliet et al. 2004; Bare et al. 2012). Converting midpoints to endpoints simplifies the interpretation and understanding of the LCIA results, however, aggregation increases uncertainty in the results since causal links between emissions and impacts often become weaker as complexity increases (Bare et al. 2012; Bonou et al. 2016). The LCIA methods such as CML 2001, IMPACT 2002+, ReCiPe 2008, and ILCD 2009 methods are used to transform LCI data into LCIA results (JRC, 2010; Finnveden et al., 2009; Goedkoop et al., 2008; Park et al., 2014; Rosenbaum, 2017; Weidema, 2015; Bueno et al. 2016). These characterization methods may consider different types and numbers of areas of protection (AOP). For instance, RiCiPe 2008 accounts for damages to: human health, ecosystem quality and natural resources (Goedkoop et al., 2008). But, IMPACT 2002+ impact assessment method, in addition to the three damage areas considered by ReCiPe 2008, includes life support systems (PRé, 2018).

The selection of one method from others is not always clear. It means that it can be affected by area of study and impact categories considered (Amani and Schiefer, 2011), user's experience (Chevalier and Tatiana Reyes-Carrillo, 2011) and the availability of previous works for comparison of results (Finnveden et al., 2009). The CML, IMPACT

2002+ and ReCiPe 2008 are most commonly used LCIA method (Ekvall and Weidema, 2004). ISO standards do not provide any restriction to the choice of the LCIA method but require that we make justification on our choices. In this study, considering that the ReCiPe 2008 method has been used by previous researchers (Briones Hidrovo et al., 2017a) and we can compare results with, the same method was applied to calculate the environmental impacts. The ReCiPe 2008 method calculates potential environmental impacts of 18 and 3 midpoint and endpoint category indicators.

2.3.4. Life cycle Interpretation

Life cycle interpretation is the fourth mandatory phase in the ISO 14040 and ISO 14044 standards and defined as the "phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations." (ISO 2006a, 2006b). According to Curran (2015), the purpose of the interpretation phase is to give credibility to the results of the LCA studies by the intended users that involves identifying and evaluating significant issues affecting the results. The interpretation phase can also be used to trigger efforts towards improving LCI and LCIA models (Hauschild et al., 2018). Therefore, this phase of LCA evaluates the results of preceding stages and reports the findings in the form of conclusions and recommendations for the intended users of the study.

According to ISO 14044 standard, the interpretation phase involves three steps that should be done iteratively until the conclusions are consistent with the requirements of the goal and scope of the study. The first step identifies significant issues related to methodological choices and assumptions (e.g., functional unit, cut-off criteria, allocation, impact assessment methods, impact categories, lifespan, and waste disposal options) made during goal and scope definition; inventory data (both input and output flows) for key processes during inventory analysis; characterization and normalization factors in impact assessment phase (ISO, 2006b; Zampori et al., 2016; Hauschild et al., 2018). The second step assesses the identified significant issues for completeness (e.g., check for availability and adequacy of data for key processes identified), sensitivity (i.e., check for the stability of the final results to changes in significant issues) and consistencey (e.g., check for choices and assumptions are applied consistently throughout the LCA as defined in the goal and scoping phase) (Curran, 2015). The last step of the interpretation phase draws conclusions, explains limitations and provides recommendations of the overall LCA study.

Zampori et al. (2016) and Hauschild et al. (2018) recommended that the identification and evaluation of significant issues can be performed using analytical tools such as sensitivity and scenario analyses. They suggested that most important processes, impact categories, characterization and normalization factors and impact assessment methods can be identified and ranked by running sensitivity analysis by varying single issue or by joint variation of combined issues depending on their interdependence. Hauschild et al. (2018) have also proposed that a scenario analysis can be used to identify and evaluate significant choices and assumptions based on their effects on the final LCI / LCIA results.

Although LCA is known as an important tool for understanding environmental performance and making informed decisions of products, materials and processes, it is liable to several uncertainties related to qualities of data used and choice and assumptions made in the LCA process. According to Bjrklund (2002), uncertainty is a result of lack of knowledge on the true value of a quantity and it is different from variability, which is because the heterogeneity nature of values (e.g., difference on emission inventories stem from spatial and temporal variations). She further explained that the former can be minimized by acquiring more reliable and more accurate data, whereas the latter can be reduced by better sampling in ranges of space and time. But often the concept of 'uncertainty' refers to both uncertainty and variability (Wei et al., 2014). Huijbregts et al., (2003) classified LCA uncertainties generally into three types: parameter uncertainty (i.e., uncertainties due to input data quality), model uncertainty (i.e., uncertainties due to the fact that models do not describe real system exactly) and scenario uncertainty (e.g., uncertainties attributed to choices of methods). Therefore, the other underlying reason that results of the LCI / LCIA phases shall be interpreted is to understand the uncertainty of the results (ISO, 2006b).

There are various methods and approaches to identify, evaluate and manage uncertainties. These include standardization of methods, critical review, sensitivity analysis, uncertainty importance analysis, scenario analysis, Monte Carlo simulation (Bjrklund, 2002; Murphy, 2016). Hauschild et al. (2018) recommend that sensitivity analysis and uncertainty analysis should be performed simultaneously that allows focusing on influential data, but with high uncertainty to bring improvement in the LCA data. Using a case study, Huijbregts et al. (2003) illustrated that different types of uncertainties affect the LCA output and stressed the importance of quantifying parameter, scenario, and model uncertainty simultaneously.

2.4. LCA software and databases

An LCA study relies on the models of the real system, which consists of a number of processes throughout the life cycle stages of analyzed system. Due to cost and time, it could be difficult to collect all input and output flows of these processes and to calculate manually the environmental loads. LCA software and LCA databases are helpful to reduce these burdens. The LCA software packages are used to design system models, compute LCI and LCIA results and visualize results in different formats. The databases provide the background data and are the backbone of all calculations. Ciroth (2012) reviewed available LCA software and databases and acknowledged that performing LCA would have been difficult without these tools. Curran (2015) agrees with Ciroth by saying "there are no LCA results without [LCA] software". This encouraged that LCA software packages to evolve significantly from general spreadsheet models to LCA software packages integrated with elaborated LCA databases (Curran, 2015).

Today there are several LCA software packages, the most commonly used are GaBi, SimaPro, Umbero and OpenLCA (Curran, 2015; Murphy, 2016; Aparecido et al., 2019). Because these software packages are developed regardless of type, size and scope of the project, they may give different results for the same product. For the same product system, Aparecido et al. (2019) compared GaBi, SimaPro, Umbero and OpenLCA and found different LCA results attributed to the use of different background data and characterization factors. Similarly, Herrmann and Moltesen (2014) and Speck et al. (2015) compared GaBi and SimaPro and realized that in certain cases they give different results. Seto et al. (2017) recommended that LCA software packages should be selected based on their 'flexibility, sophistication and complexity of analysis, and usefulness of outputs'. In summary, LCA software packages and databases are developed to help the LCA analyst; but the analyst should be aware of their inherent strengths and weaknesses, in addition to have the basic knowledge of LCA methodology and the system to be analyzed.

2.5. Compilation and computational methods

According to ISO LCA standards (ISO, 2006a , 2006b) for LCA , a unit process is the smallest portion of a product system for which data are collected and compiled when performing an LCI/LCA analysis. The **Figure 2.1** depicts a generic unit process with potential inputs (materials and energy) on the left and potential outputs (e.g., wastes, emissions, co-products, and target products) on the right.

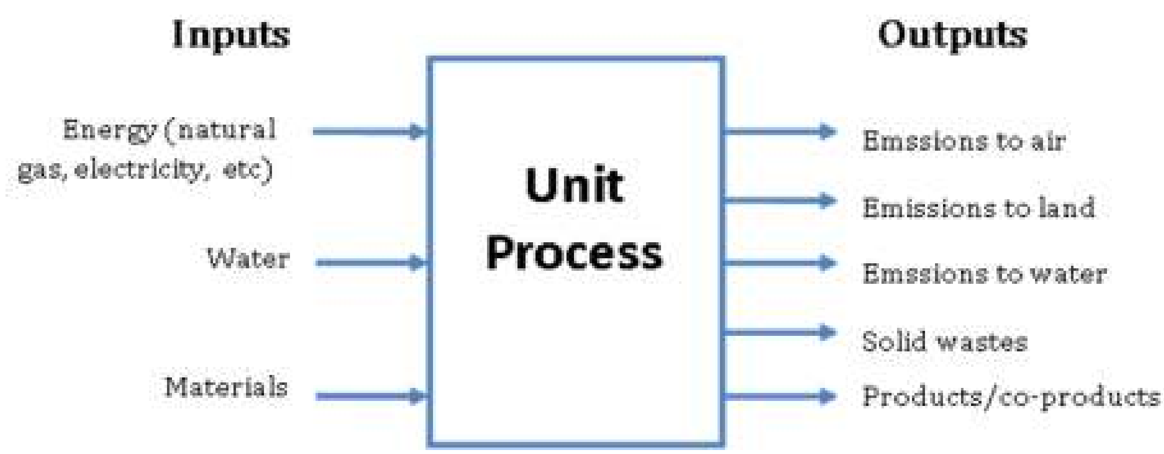


Figure 2.1 A generic representation of a typical unit process with possible input and output flows

As illustrated in **figure 2.2** below, the data entry interface of SimaPro LCA software (thus the integrated databases like Ecoinvent) is structured in such a way that input and output flows (inventories) of a unit process are compiled as follows: inputs from nature, inputs from the technosphere, outputs to nature, and outputs to the technosphere. Inputs from nature refer to flows extracted from the ground or natural environment (e.g., crude oil, stone, raw wood). Conversely, outputs to nature refer to pollutants and wastes that are released back into the environment. Inputs from and outputs to the technosphere refer to any flow of energy or mass that originates from a man-made process (e.g., diesel fuel, crushed gravel, timber). In SimaPro software, the output to technosphere flows also include the main and co-products.

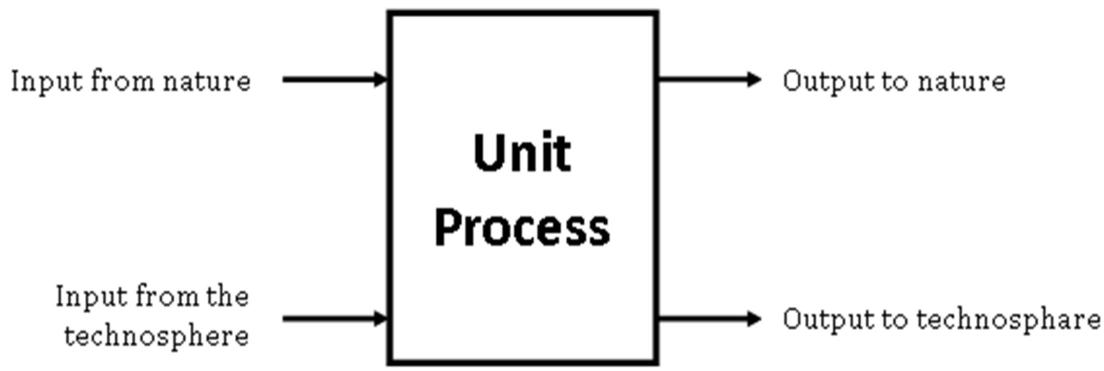


Figure 2.2 Schematic representation of the unit process and types of flows

The compilation structure of unit processes in the LCI models determine the computational methods of inventory analysis. Unit processes in process-based LCI models can be compiled across process flow diagrams or in matrix form and thus generally there are two common LCI computational methods: namely sequential and matrix methods (Suh and Huppes, 2005; Bourgault et al., 2012). In sequential method, the compilation and computational structures follow the process flow diagram of analyzed system in series. This is the common and simple inventory analysis method when there are no feedback loops in the system. For instance, if the production of electricity steam requires steel, and production steel requires electricity. In such cases, sequential method of computation will be difficult and time-consuming, especially for manual calculations. First introduced by Heijungs (1994) to solve drawbacks in sequential method, the matrix (inversion) method applies basic matrix notations and computational rules, where unit processes and associated environmental interventions are compiled in matrix forms. The basic procedures of sequential and matrix inversion methods with examples are given in **Annex A.** Detail information on LCI computational methods are available (Heijungs and Suh, 2002; Suh and Huppes, 2005; Peters, 2007; Yan et al., 2013; Ocampo et al., 2015).

For process-based LCA, either sequential or matrix inversion methods can be used depending the LCA software being applied. For instance, GaBi software applies the sequential method, whereas SimaPro LCA software uses matrix inversion method (Suh and Huppes, 2005). On other hand, the matrix inversion method is the most appropriate computational method in EIO-LCA (Chris and Horvath, 1998; Kitzes, Suh and Huppes, 2005; 2013). Once the aggregated LCI values are computed, as stated in section 2.3.3, they are converted into impacts (e.g., climate change or acidification) using characterization factors integrated in the impact assessment method selected.

2.6. Electricity systems and LCA studies

2.6.1. General

Electricity has become vital in modern society. Despite its importance to modern life, studies show electricity generation from all sources cause adverse impacts on human heath, ecosystems and natural resources (Wilkinson, 2001; Markandya and Wilkinson, 2007; Henderson, 2018). LCA has been applied to identify and evaluate environmental performance of electricity (Gagnon et al., 2002; May and Brennan, 2003; Denholm and Kulcinski, 2004; Kim and Dale, 2005; Di et al., 2007; Lund and Biswas, 2008; Turconi et al., 2013; Amponsah et al., 2014; Liu, 2014; Pang et al., 2015; Yuguda et al., 2020).

Based on the decision context, Laurent et al. (2018) distinguish between micro-and macro-scale LCA studies for electricity systems. They suggested that micro-scale LCA studies deal with individual electricity technologies/sources at power plant level. For instance, the LCA can be performed for a single or group of hydropower plants aiming at understanding their overall environmental burdens to generate 1kWh electricity. The results of micro-scale LCA studies can be used to initiate improvement options on significant processes or 'hot spots' throughout similar electricity system or may be used to compare different electricity technologies to support decisions related to specific electricity technologies/sources. On other hand, macro-scale LCA studies are used to assess environmental impacts associated with electricity generation (from different sources) of a given country (e.g., generation/consumption of 1kWh electricity). Besides to estimate the overall environmental impacts of an electricity mix of a given country/region in certain time, macro-scale LCA studies can help policy analysis by comparing different scenarios or plans of electricity generations and thus they support macro-scale decision-and policy-making.

Laurent et al. (2018) further identified two perspectives in LCA studies, namely retrospective and prospective. They define that prospective LCAs are change-oriented studies that assess (present or future) overall environmental impacts of an electricity system incorporating possible changes or scenarios. On the other hand, retrospective LCA studies are used to estimate (past, present or future) overall environmental impacts of an electricity system for business-as-usual scenario. In this case, retrospective studies can serve as baseline scenario to compare with the prospective studies. According to Tillman (2000), the retrospective (accounting) LCA studies describe the environmental impacts of the analyzed system (e.g., an electricity system) as it exists, whereas prospective LCA studies model the effects of any changes in the analyzed system. Close looks to these two literatures show that there is a difference on the definitions of prospective LCAs. According to Laurent et al. (2018), prospective LCA studies refer to overall environmental impacts of analyzed system but with some changes compared to baseline scenario (e.g., change in technology mix). However in Tillman (2000), prospective LCA studies considers only those processes affected by any change on the system (e.g., change in demand). The latter is similar to consequential life cycle assessment (cLCA) which models the effects of changes to estimate marginal environmental impacts of the analyzed system.

2.6.2. Hydropower systems

2.6.2.1. Classification

Hydropower plants convert kinetic energy of flowing water into mechanical energy and then into electrical energy using turbines and generators respectively. In LCA modelling, hydropower plants are commonly classified into different groups based on storage facility, size, function and location. In terms of storage facilities, they are classified as reservoir and run-of-river (ROR) type. A reservoir hydropower plant requires a dam to store water, which is allowed to flow via the turbine when there is a demand to electricity. On other hand, a ROR system does not have storage facility; rather depends on the actual amount of river water flow. Reservoir and ROR hydropower plants are preferred to fulfill peak-and base-demand of electricity respectively.

In terms of power generation capacity or size, hydropower plants can be classified as micro-, small-and large-scale HPPs. However, there is no international consensus on size definitions of small hydropower (SHP) plants, they vary from country to country based on national policies (Elbatran et al., 2015; IPCC, 2011; Khan, 2015). For instance, in Sweden small-scale HPPs represent schemes with installed capacity less than 1.5MW, Norway (≤10

MW), India (≤ 25 MW), Brazil (≤ 30 MW), Canada and China (≤50 MW) and between 5 and 100 MW in U.S (Elbatran et al., 2015). Kadiyala et al. (2016) proposed different size classifications: micro-HPPs are those whose power generation capacities are below 0.1 MW, whereas small and large refer to between 0.1 - 30 MW and greater than 30 MW HPPs respectively. Tkáč (2018) has also proposed size classification as pico (<5 kW), micro (5 - 100 kW), mini (100 kW - 1 MW), small (1 - 25 MW), medium (25 - 100 MW) and large (100 - 500 MW) and very large (>500 MW). In Ethiopia, there is no officially recognized size definition for hydropower projects and thus different studies used different size classifications. Varun et al. (2010) classified hydropower plants 10 MW as divide-line for small and large hydropower plants, while Dametew (2016) categorized as small-scale (<40 MW), medium-scale (40 - 60 MW) and large-scale (>60 MW).

Another classification of hydropower plants is based on the locations of reservoirs as tropical, non-tropical or alpine regions; because greenhouse gas emissions from reservoirs depend on climatic conditions (Treyer and Bauer, 2013).

2.6.2.2. LCA studies

Studies revealed that hydropower has considerable direct (i.e., those related to their construction and operation) and indirect (i.e., those that arise from value chain of materials and products) ecological and social impacts that should not be ignored (IPCC, 2011; Botelho et al., 2017). The direct impacts include damage on fauna and flora, landscape disturbance, siltation, displacement of people and risk of failure. These direct and local impacts can be identified and evaluated using relevant environmental impact assessment methods and proper mitigation measures could be incorporated during planning phase. On other hand, the indirect impacts arise due to natural resource consumptions and emissions during their life cycle stages. These indirect and global impacts should be examined using life cycle-based approaches. More important, these impacts are highly dependent on site conditions, type and size of hydropower plants (Kaunda et al., 2012).

There are many LCA studies on hydropower systems. Their objectives can be either (1) evaluation of their environmental performance for single or group of parameters, (2) evaluation of effects of capacities and types of construction within hydropower plants, (3) comparison of their environmental impacts with other technologies/sources. For instance, Raadal et al. (2011), Jing Zhang et al. (2015) and Kadiyala et al. (2016) performed LCA focusing on GHG emission; Mekonnen and Hoekstra (2012), Bakken et al. (2016) and Zhang et al. (2018) on water footprint; (Zhang et al., 2007) on energy and GHG emission intensities and Ribeiro and da Silva (2010) and Pang et al. (2015) dealt on several of these factors of hydropower system. Other LCA studies have been used to compare effect of size, type and location on the impacts of hydropower systems. Zhang et al. (2007), Bakken et al. (2016) and Atilgan and Azapagic (2016) claimed that impacts of large hydropower systems are lower than smaller ones for the same energy output because larger projects usually have a longer lifespan as well as greater output. Moreover, Zhang et al. (2015) evaluated two hydropower systems: one with earth-core rockfill dam (ECRD) and the other with concert gravity dam (CGD) and found that the former is more environmentally friendly than the later one. Wanga et al. (2019) performed a comparison LCA between hydro, nuclear and wind power systems.

According to Raadal et al. (2011b), besides 'true' project variations such as height of heads and site of construction (which affects reservoirs GHG emissions), methodological choices and assumptions such as system boundaries and lifespan may affect the impacts of hydropower facilities. Similarly, Egré and Milewski (2002) suggested that allocation should be considered for multiple functions such as flood control, irrigation, water supply, recreation, fishing and navigation. As shown in **Table 2.2** blow, in terms of modelling approach, most case studies applied the process-based retrospective or attributional LCA method. Zhang et al. (2007) and Bhat and Prakash (2014) have used retrospective but economic input-output (EIO) LCA. In addition, different LCA studies applied different lifetimes for hydropower plants, regardless of their scale and type classification. For example, Zhang et al. (2007) and Hidrovo et al. (2017b) used a lifespan of 50 and 100 years respectively for two medium-scale hydropower schemes. Similarly, Hidrovo et al. (2017b) and Vougioukli et al. (2017) applied 50 and 80 years for two ROR type hydropower schemes. In addition, the reviewed literatures did not perform any allocation procedure.

Although the environmental performance of HPPs depend on their types, sizes and locations there are few studies for Africa (Gujba et al., 2011; Brizmohun et al., 2015), which are based on LCI data from secondary sources and database. To the knowledge of this author, there is no reported LCA study on hydroelectric generation technologies from Africa in general and Ethiopia in particular.

Table 2.2 Examples of LCA of hydropower plants of previous studies

References	location	Category	Capacity (MW)	Size	Lifetime (years)	GWP ($gCO_{2\,eq.}$)	ADP (gSb_{eq})	AP ($gSO_{2\text{-}eq}$)	EP ($PO_4^{3-}{}_{eq}$)	HTP (g1.4-DBeq)	FAEP (g1.4-DBeq)	POCP (gC_2H_4eq)	TEP (g1.4-DBeq)	FD (g $oil_{eq.}$)	LCIA Method
Skone et al. (2012)*	US	Reservoir	2080	VL	80	43.8									p-LCA
Wanga et al. (2019)	China	Reservoir	252	VL	50	4		0.016	0.005	2		0.0016			p-LCA
Zhang et al. (2007)	China	Reservoir	3600	VL	100	6								0.176	EIO-LCA
Flury and Frischknecht (2012)	Europe	Reservoir	96.00	L	150	11	0.0200	0.015	0.006	8	1.9630	0.0010	0.0230	0.881	p-LCA
Hidrovo et al. 2017)	Ecuador	Reservoir	42	M	100	6		0.010			0.0200		0.0003	0.880	p-LCA
Geller and Meneses (2016)	Brazil	Dam-toe	30	M	100	5	0.0312	0.022		7	2.4505				p-LCA
Zhang et al. (2007)	China	Reservoir	44	M	50	44								1.156	EIO-LCA
Pang et al. (2015)	China	Weir	3	S	30	28	0.0916	0.109		11	4.1000	0.0093			p-LCA
Suwanit and Gheewala (2011)	Thailand	Weir	5	S	50	11	0.7639	0.057		23	4.5800	0.0029			p-LCA
	Thailand	Weir	6.00	S	50	23	0.1500	0.117		40	7.6200	0.0065			p-LCA
	Thailand	Weir	2.50	S	50	16	0.1015	0.077		33	6.9700	0.0046			p-LCA
	Thailand	Weir	2.25	S	50	23	0.1516	0.110		28	6.9700	0.0075			p-LCA
	Thailand	Weir	1.15	S	50	16	0.1047	0.080		52	9.0800	0.0045			p-LCA
Hidrovo et al. (2017)	Ecuador	ROR	21	S	80	3		0.008			0.0210		0.0001	0.600	p-LCA
Flury and Frischknecht (2012)	Europe	ROR	8.60	S	80	4	0.0190	0.015	0.006	8	2.0470	0.0010	0.0290	0.833	p-LCA
Bhat and Prakash (2014)	India	ROR	3	S	30	35									EIO-LCA
Hanafi and Riman (2015)	Indonesia	ROR	9	S	50	1									p-LCA
Gallagher et al. (2015)	UK	ROR	1	Mini	50	5	0.0001	0.041		16				0.004	p-LCA
Bhat and Prakash (2014)	India	ROR	0.10	Mini	30	55									EIO-LCA
Gallagher et al. (2015)	UK	ROR	0.05	Micro	50	9	0.0002	0.079		31				0.004	p-LCA
Gallagher et al. (2015)	UK	ROR	0.10	Micro	50	7	0.0002	0.059		21				0.004	p-LCA
Bhat and Prakash (2014)	India	ROR	0.05	Micro	30	75									EIO-LCA
Navarro-Pineda et al. (2017)	Mexico	Mixed		Mixed		30	0.0481	0.012	0.0763	94	23.0000	0.0058	3.2700		p-LCA
Raadal et al. (2011)	Review	Reservoir				0.2-152									
Raadal et al. (2011)	Review	ROR				0.5-9.3									

*Capacity of hydropower plant (The capacities of the nuclear and wind power are … respectively)
** Lifespans used: Reservoir hydropower plants = 150 years; run-of-rive hydropower plants = 80 years; wind farms = 20yers. Life span for geothermal is not explicitly defined.
R= reservoir and ROR= Run-of-river

2.6.3. Wind power

2.6.3.1. Classifications

Based on previous studies, Kadiyala et al. (2017) classify wind turbines into different categories based on their axis of rotation and installed location. Based on axis of rotation of the blades, wind turbines are divided into two, namely horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT). In HAWT, blades are horizontal (parallel) with the ground, whereas in VAWT, they rotate vertically (perpendicular) to the ground. In terms of location of installation, wind turbines can be further classified as onshore (i.e., wind turbines are installed over the land and offshore (i.e., the wind turbines are installed in shallow waters off the coastal areas). Using modes of control, wind turbines can also be classified as fixed speed; e.g., directly grid coupled squirrel cage induction generator wind turbines, and variable speed wind turbines; e.g., doubly fed induction generators (DFIG) wind turbines (Atallah and Bayoumi, 2015). Depending on the configuration of drive train, they can still be sorted as with and without gearbox wind turbines (Polinder et al., 2006; van de Kaa et al., 2020) and based on their electricity generation capacity (Arvesen and Hertwich, 2012) as Small (≤ 0.1MW), Medium (0.1 - 1 MW) and large (>1MW). Today, the HAWT, variable speed and with gearbox wind turbine generators are the more widely adopted wind turbines in the wind industry, but the offshore wind turbines gaining prominence because better wind conditions in large water bodies (Wang and Sun, 2012; Kadiyala et al., 2017).

Wind farms are composed of a large number of individual wind turbines, of similar or different types of wind turbines. Depending on their installed capacity, wind farms can be categorized as follows: Small (up to 10 MW), medium (up to 40 MW), large (up to 100 MW) and extra-large (≥100 MW) (ENERGIE, 2001).

2.6.3.2. Wind power and energy

A wind turbine is the smallest unit in wind power that generates power and energy. It converts the kinetic energy of the wind to mechanical energy and then to electricity. The three main components for energy conversion in a wind turbine are rotor, gearbox and generator. The rotor converts the fluctuating wind energy into mechanical energy and is thus the driving component in the conversion system. The generator absorbs the mechanical power and converts it into electrical energy. In a wind turbine with gearbox, the gearbox adapts rotor to generator speed. The slow moving direct drive permanent magnet generators (DDPMG) wind turbines do not need gearboxes (ENERGIE, 2001). At wind turbine generators level, the maximum voltage produced is 400 or 690 V. Depending on the demand, the generator is either directly connected to the grid (if the demand is for low voltage ≤ 0.1 kV) or series of medium and high voltage transformers to satisfy requirements for medium voltages (0.1- 0.35 kV) and high voltages (≥ 0.35 kV) (ENERGIE, 2001).

According to Glassbrook et al. (2013), there are two approaches to estimate the potential power output of wind turbines. The first approach uses a power curve, which is power output verses wind speed graph provided by manufacturers for each turbine for a range of wind classes. Knowing the average wind speed of a project site, thus one can read the power from the power curve. In case the power curve of the wind turbine is absent or unreliable, the power output can be calculated from half the product of swept area of the turbine (i.e., the area swept by the turbine rotors), third power of the wind speed of the site and the overall efficiency of the turbine. According to Asdrubali et al. (2015), the energy production over a time interval can be computed as summation of the product of power with time (e.g., in one hour interval)

2.6.3.3. LCA studies of wind power

Wind power systems have lower environmental impacts during operation phase; but they do have quantifiable local and global impacts during manufacturing, construction and end of life phases (Saidur et al., 2011; Demir and Akif Tas, 2013; Wang, Wang, & Smith, 2015b).The local impacts of wind power, such as noise pollution and damages to birds are addressed in many studies (Saidur et al. 2011; Kaldellis et al. 2012; Leung and Yang 2012b; Wang and Wang 2015; Wang et al. 2015b). However, the potential global environmental impacts (e.g., climate change, acidification etc.) of wind power should be evaluated from systematic perspective, covering all life stages from cradle to grave. A number of life cycle assessment (LCA) studies have also been conducted to evaluate such potential environmental impacts of wind turbines or wind farms. Some of LCAs dealt with individual wind turbines aiming at evaluating and comparing different sizes (e.g., Tremeac and Meunier, 2009; Demir and Akif Tas, 2013; Vargas et al., 2015) or different wind turbine models (e.g., Guezuraga et al., 2012; Haapala and Prempreeda, 2014; Schreiber et al., 2019). Other LCAs focused on impacts of wind farms, rather than individual wind turbines. Since the motivation of this study is to evaluate the environmental impacts of wind farms, only LCAs of wind farms are included in this review.

LCAs for wind farms typically have one of the following goals: evaluating only wind farms or comparing wind farms with previous LCAs of wind power. For example, Ardente et al. (2008) evaluated the energy and environmental performance of an Italian 22 MW onshore wind farm consisting of 0.66 MW wind turbines. Yang & Chen (2013) have assessed the embodied energy, greenhouse emissions and economic performance of a typical 49.5 MW onshore wind farm in China comprised of 1.5 MW wind turbines. Oebels and Pacca (2013), Palomo et al. (2014), and Abeliotis and Pactiti (2014) have examined the life cycle environmental performance of wind farms in Brazil, France and Greece respectively. More specific case studies have been conducted in recent years. Ji & Chen (2016) estimated the overall carbon footprint of a 48 MW wind farm in China composed of 2 MW wind turbines using LCA and input-output analysis (IOA). Xu et al. (2018) have studied a 49.5 MW onshore wind farm with Goldwind 1.5 MW and 0.75MW wind turbines from a cradle to grave perspective. They concluded that there is no direct relationship between the size of the turbines and the life cycle environmental impacts, although large size turbines improve most environmental impact indicators compared to smaller ones. LCA has also been applied to a 50 MW wind farm in Spain composed of 2.0 MW wind turbines to prepare an environmental product declaration (IBERDROLA 2018). Ozoemena et al. (2018) have applied LCA to examine the potential environmental impacts of a 114 MW onshore wind farm in Wales (UK) consisting of Enercon E-66 1.5 MW wind turbines and other four design variants to evaluate technology improvement opportunities.

On the other hand, Wanga et al. (2019) compared the environmental impacts of hydro, nuclear and wind energy systems and they found that wind power generates more GHG emission than hydro and nuclear power systems. Similarly, Raadala et al. (2011) conducted a comparison assessment of environmental impacts of Hydro and wind power based on the results of previous studies. There are also meta-analyses of wind power LCA studies (e.g., Arvesen and Hertwich 2012; Dolan and Heath 2012; NREL 2013; Kadiyala et al. 2017). It is worth stating that most of the above LCA studies are limited to the circumstances of China, Europe and North America. Only few LCA studies of wind farms are available in Africa (e.g., Al-Behadili and El-Osta 2015). Furthermore, no LCA data has been found for wind farms in Ethiopia.

Table 2.3 presents relatively detailed information of wind farm LCAs discussed above. It can be seen that different capacity factors and impact categories are considered in most works, with exception that all studies estimated GWP. There are also differences in defining system boundaries and assumptions considered. For instance, Oebels & Pacca (2013) and IBERDROLA (2018) did not clearly specify their impact assessment methods. IBERDROLA (2018) included the recycling of materials like metals and plastics in the LCA, but Wanga et al. (2019) did not at all. Most LCAs have assumed 20-year lifespan for wind farms, but IBERDROLA (2018) used 25 years. All these may affect the consistency and comparability of results as shown in table 3 below.

Table 2.3 Life cycle assessment case studies of wind farms

References	location	Type	No. units	Unit capacity	Total capacity	Lifetime (years)	CF (%)	Impact categories	LCIA methods
Yang and Chen (2015)	Mongolia	Onshore, geared	33	1.5	49.5	20	25.8	GWP, EROI, EPBT	Arithmetic
Xu et al. (2018)	China	Onshore, gearless	18	1.5	27	20	30	GWP	pLCA, CML 2001
Wanga et al. (2019)	China	Onshore	33	1.5	49.5	20	23.7	GWP, AP, EP, HTP, POCP	pLCA, CML 2001
Wang and Sun (2014)	China	Onshore, geared	186	1.65	306.9	20	40.7	GWP	pLCA, CML 2 BL 2000
Palomo et al. (2014)	France	Onshore, geared	5	3	15	20	-	GWP, ADP, AP, EP, POCP, ALO, ULO, NLT,	pLCA, CML and ReCiPe 2008
Ozoemena et al. (2018)	UK	Onshore, geared	76	1.5	114	20	22	GWP, ADP, AP, EP, OLDP, HTP, FAEP, TEP,	pLCA, CML 2 BL 2000
Oebels & Pacca (2013)	Brazil	Onshore, geared	14	1.5	21	20	34.25	GWP	Not specified
Ji & Chen (2016)	China	Onshore, geared	24	2	48	20	25.8	GWP	EIO-LCA
IBERDROLA (2018)	Spain	Onshore, geared	25	2	50	25	98	GWP, ADP, AP, EP, OLDP, POCP	Not specified
Garrett and Rønde, (2013)	Typical	Onshore, geared	25	2	50	20	25.8	GWP, ADP, AP, EP, HTP, FAEP, POCP, FD, EPBT	pLCA, CML 2 BL 2000
Ardente et al. (2008)	Italian	Onshore, geared	11	0.66	7.26	20	19.04	GWP, AP, EP, OLDP,	
Al-Behadili and El-Osta 2015	Libya	Onshore, geared	37	1.65	61.05	20	42.4	GWP	Arithmetic
Abeliotis & Pactiti (2014)	Greece	Onshore, geared	4	0.85	3.4	20	35.6	GWP, ADP, AP, EP, OLDP, HTP, FAEP, TEP,	pLCA, CML 2 BL 2000

Key:

- *Global Warming Potential (GWP), Abiotic Depletion Potential (ADP), Fossil Depletion (FD) Acidification Potential (AP), Eutrophication Potential (EP), Fresh Aquatic Ecotoxicity Potential (FEEP), Human Toxicity Potential (HTP), Terrestrial Ecotoxicity Potential (TEP), Photochemical Ozone Creation Potential (POCP), Agricultural Land Occupation (ALO), Urban Land Occupation (ULO), Natural Land Transformation (NLT), Cumulative Energy Demand (CED), Energy Payback Time (EPBT)*
- *Capacity factor (C), Process-based life cycle assessment (pLCA) and economic input-output life cycle assessment (EIO-LCA)*

2.7. Application of LCA of Electricity

The results LCI and LCA studies of electricity have many applications. First, they are useful for understanding and identification of 'hotspots' that support operational improvement of analyzed systems (Günkaya et al., 2016; Paulillo et al., 2019; Magdalena and Kulczycka, 2020). Second, LCA data are used for comparing electricity technologies (e.g., WNA, 2011; Jin Zhang et al., 2015;Wanga et al., 2019). Third, communication tools such as Environmental Product Declaration (EPD) of electricity systems (e.g., Vattenfall-AB, 2013b) are based on LCA data of electricity. EPD is a tool resulting in a verified environmental data over the life cycle of products in accordance with the international standard ISO 14025:2006 (Del Borghi, 2013). Finally, the LCA data is also useful to perform LCA studies of other products for electricity is an important input in almost all products, thus it can support in product and process development. However, electricity LCI/LCA data depends on electricity mixes of countries (Suksuntornsiri and Limmeechokchai, 2005) and existing LCA studies are limited to conditions of developed countries (Turconi et al., 2013a). In addition, according to World Energy Council (WEC, 2004), they are highly affected by methodological choice and assumptions used by particular studies that make difficult for making comparison between. Therefore, development of representative and up-to date LCI datasets will remain important in order to improve LCA results (Treyer and Bauer, 2016a, 2016b) and as there is a need to improved electricity technologies with reduced environmental impacts (Masanet et al. 2013).

2.8. Summary

In order to incorporate environment concerns into decisions, reliable environmental information of existing or proposed actions is important. This in turn requires understanding the actions and their alternatives (i.e., problem definition), evaluation of alternatives and selection of alternative(s) with less environmental impacts. Thus, environmental assessment is used to evaluate environmental implications of human activities to support decision-makers using different tools developed to address different aspects of human actions. LCA is one of these tools used to evaluate the environmental aspects and impacts of products (goods and services) throughout their life cycle stages regardless of space and time. It is preferred to avoid of problem shifting across various chains of the product. It is a well-established and standardized method that involves goal and scope definition, inventory analysis, impact assessment and interpretation.

LCA has been used to evaluate the environmental impacts of electricity generation technologies/sources both from retrospective (accounting) or prospective (change-oriented) perspectives. The retrospective LCA studies aim at describing how the analyzed system was/is/will be working, whereas the prospective LCA studies aim at studying the effects on the analyzed system due actions on the analyzed system or systems linked to it. The results of LCI/LCA studies of electricity system support operational improvement, strategic planning, communication/marketing and product and process development. From the reviewed LCA studies of hydro and wind power systems:

- LCAs based on retrospective perspective system modelling and process-oriented data collection and compilation have been commonly applied.
- Type and number of impact categories are defined by the researchers
- There is no uniformity in methodological choices and assumptions
- Although there are other values, lifespan of 50 and100 years are common for small and large hydropower pants respectively; and lifespan of 20 years for wind LCA.

The case studies in chapter 3 and 4 are mainly organized in line with the ISO standardized LCA framework that involves four main steps: goal and scope definition, inventory analysis, impact assessment and interpretation. Various methodological choices and assumptions are considered. A process-based attributional LCA is applied using SimaPro software version 8.0.1 and ReCiPe 2008 as life cycle impact assessment (LCIA) method. Lifespans of 100 and 20 years are assumed for all hydropower plants and wind farms respectively. The effects of choices and assumptions on the final outputs are checked using sensitivity and scenario analyses. In addition, chapter 5 syntheses the LCA models developed in chapter 3 and 4 and compares key LCI and LCIA impacts of hydro and wind electricity generation technologies.

3. LIFE CYCLE ASSESSMENT OF ETHIOPIAN HYDROPOWER SYSTEMS

Abstract

This study presents the life cycle assessment (LCA) of environmental impacts of Ethiopian hydropower system from eleven hydropower plants (HPPs). The environmental impacts per kWh of electricity generated were estimated using process-based attributional LCA approach from cradle-to-grave perspective using SimaPro software and ReCiPe 2008 impact assessment method.

The results showed that climate change (32 g CO_2 eq.), human toxicity (0.58 g 1, 4-DB eq.), metal depletion (1.04 g Fe eq.) and fossil depletion (0.82 g oil eq.) were some of the major environmental impacts. The results revealed that medium-scale HPPs have higher environmental impacts than large-scale HPPs. In both cases, the construction and installation phase contribute the major share (62-99%) in most impact indicators. The contribution of transportation is small that ranges from 1 to 2%. Importantly, end-of-life recycling of metal scraps would reduce metal depletion by 27%. The results of the sensitivity analyses showed that the choice of design period and production efficiency of HPPs would significantly affect LCA results.

The findings from this study hopefully help proper selection of installed capacities, design periods and waste disposal options of HPPs. Moreover, the results could be used by researchers and practitioners as input for the national energy system LCA studies.

3.1. Introduction

Renewable energy sources are considered as promising options for mitigating energy security and ensuring environmental sustainability. Hydropower is one of the renewable power generation technologies with considerable potential to reduce net fossil-based greenhouse gas emissions next to solar and biomass (Ahmad and Tahar, 2014). Hence, hydropower plays an important role in renewable power generation worldwide. According to the 2019 reports of the International Renewable Energy Agency (IRENA, 2019a) and International Hydropower Association (IHA, 2019) , the global total installed hydropower capacity in 2018 was 1292.4 GW, which was 55% of the total renewable power. According to these reports, the new hydropower capacity put into operation in 2018 was around 21.8 GW where China added the largest capacity (8.5 GW), followed by Brazil (3.9 GW) and Pakistan (2.5 GW. In the same year, total hydropower installed capacity in Africa was 36.7 GW, which was 8.4% higher compared to the year 2017. Ethiopia, South Africa, Angola, Egypt and Congo Democratic Republic have the highest developed hydroelectric power with an aggregated installed capacity of 16.1 GW that represents 43.9% of the installed capacity of the region.

The existence of many large rivers that flow from highlands to lowlands endowed Ethiopia a huge hydropower potential. Ethiopia is often described as the water tower of northeastern Africa. The gross, technical and feasible hydropower potentials of the country are about 74, 45 and 18 GW respectively, which are equivalent to about 954, 286 and 143 TWh electricity per year (MoWE, 2012a; Tucho et al., 2014). The current hydropower installed capacity has reached 3822 MW (IHA, 2019), which is only 8.5% of the technically feasible hydropower potential. Ethiopia is developing hydropower plants, as it is relatively cost effective, not only to fulfill the domestic needs but also to export surplus electricity to the neighboring countries. There are big hydropower projects that are under construction, including the halfway finished Grand Ethiopian Renaissance Dam (GERD), probably the largest hydroelectric power plant in Africa with capacity of 6350 MW (IHA, 2019). With the objective to meet domestic energy demand and climate change control initiatives, the government has set its climate resilient green economy (CRGE) strategy implementation plans to develop hydropower up to 22,000 MW by 2030 (National Planning Commission, 2016).

Hydropower plants convert the potential or kinetic energy of water into electricity. They don't burn fuel to generate energy and hence they have low environmental impacts compared to conventional fuel-based energy technologies. However, studies revealed that hydropower development has considerable direct and indirect ecological and social impacts (IPCC, 2011). The direct impacts include disruption of river ecosystems and habitants due to damming of rivers, siltation, and displacement of people and risk of failure. These direct and local impacts can be identified and evaluated using relevant environmental impact assessment methods and proper mitigation measures could be incorporated during planning phase. On other hand, the indirect impacts arise due to natural resource consumptions and emissions during their life cycle stages. These indirect and global impacts should be examined from system perspective.

Life cycle assessment (LCA) is a well-established and standardized method for identifying and evaluating potential environmental impacts of product systems throughout their life cycle stages in holistic manner (ISO, 2006a). LCA has been applied to assess overall impacts associated with energy technologies and systems on holistic perspective covering raw material extraction and production, component manufacturing, construction, operation and end-of-life waste management (Góralczyk, 2003; Masanet et al., 2013; Turconi et al., 2013b)(Lozano Miralles et al., 2020)(Wanga et al., 2019). In addition to primary actual impacts, LCA also considers induced potential impacts related to supply chains of inputs and processes. Because potential impacts may be more important than the primary ones, Pang et al. (Pang et al., 2015) recommends they should be considered if the purpose of the LCA study is to compare energy technologies or to support policy decisions. In the last two decades, LCA has been widely used to assess the environmental impacts of energy systems (Amponsah et al., 2014; Gagnon et al., 2002; Liu, 2014; Lund and Biswas, 2008; May and Brennan, 2003; Turconi et al., 2013b). Regarding hydropower generation systems, there are many LCA studies focusing on either to evaluate single impact indicator such as GHG emission (e.g., Gagnon and Van De Vate, 1997; Kadiyala et al., 2016; Raadal et al., 2011; Jing Zhang et al., 2015), water footprint (Bakken et al., 2016; Mekonnen and Hoekstra, 2012; Zhang et al., 2018) or group of these impacts like GHG emission and energy intensities (Zhang et al., 2007), or several of these factors (Pang et al., 2015; Ribeiro and da Silva, 2010). Other LCA studies presented the effect of size, type and location on impacts of hydropower systems. For instance, Zhang et al. (2007), Bakken et al. (2016) and Atilgan and Azapagic (2016), claimed that impacts of large hydropower systems are lower than smaller ones for the same energy output because larger projects usually have a longer lifespan as well as greater output. Moreover, Zhang et al. (2015) evaluated two hydropower systems: one with earth-core rock fill dam (ECRD) and the other with concert gravity dam (CGD) and found that the former is more environmentally friendly than the later one.

Most of the LCA studies on hydropower have been done in Asia (mainly in China), North America and Europe. Although the environmental performance of hydropower plants depend on their types, sizes and locations (Brizmohun et al., 2015; Bryan Karney et al., 2007; Zhang et al., 2007; Jin Zhang et al., 2015) and electricity data is vital to perform LCA studies for other product systems (Curran et al., 2005), there are only few studies for Africa (Brizmohun et al., 2015; Gujba et al., 2011) based on LCI data from secondary sources and database. There is no reported LCA study on hydroelectric generation technologies from Ethiopia. The main objectives of this study are, thus, to estimate the average LCA data for operating hydropower plants; to identify the highest contributing process to the overall impact and to compare the environmental performance of these plants with other hydropower plants studies in the world. This study would provide a significant basis for conducting LCA studies on other products and generate performance metrics such as environmental product declaration (EPD) for economically significant export products of Ethiopia. The study has also regional significance as the Ethiopian electric system has been already supplying electricity to Sudan and Djibouti and envisioned to supply to other countries in the region.

3.2. Existing hydropower plants in Ethiopia

Hydropower generation system is the main energy source of Ethiopia, supplying more than 90% of the electric energy to national grid. Currently, there are about 18 hydropower plants in Ethiopia (total installed capacity of about 4072.85MW). Of which, 15 plants are connected to the national power grid (interconnected system (ICS)) and three namely; Sor, Dembi and Yadot are off-grid hydropower plants or self-contained systems (SCS). The data collection period of this research was between 2013 and 2017, with the need to get a 5-

year average data for electricity production and resource consumption (e.g., oil). During this period, the hydropower plants such as Tis Abay I (11.5 MW), Aba Samuel (6 MW), Sor (5MW), Dembi (0.8 MW) and Yadot (0.35 MW) were not operational and others such as Genale Dawa III (265 MW) and Gibe III (1870 MW) were under construction. Therefore, this study covers the remaining 11 hydropower systems which were operating during the reference years. **Table 3.1** shows key parameters of operational Ethiopian hydropower plants including installed power capacity (IPC), maximum mean annual energy (MMAE), expected mean annual energy (EMAE) and realized mean annual energy (RMRE) generations during the reference period. The data obtained from Ethiopia Electric Power (EEP), a public enterprise in charge of generation and transmission of electricity. The realized power factors of the power stations, which is a ratio of realized mean annual energy to maximum mean annual energy (MMAE) generations found to be between 0.21 and 0.83.

Table 3.1 Capacities of hydropower plants in Ethiopia operational during base years (2013-2017)

Power stations	Year of start	IPC (MW)	MMAE (GWh)	EMAE (GWh)	RMEP (GWh)	Power factor
Amerti-neshi	2011	97	754	230	235	0.31
Beles	2010	460	3577	1720	2580	0.72
Gilgel Gibe II	2010	420	3266	1625	1570	0.48
Tekeze	2009	300	2333	1065	1040	0.45
Gilgel Gibe I	2004	184	1431	722	761	0.53
Tis Abay II	2001	72	560	359	116	0.21
Melka Wakena	1988	153	1058	543	402	0.38
Finicha	1973	134	926	760	771	0.83
Awash III	1971	32	221	182	89	0.41
Awash II	1966	32	221	182	92	0.40
Koka	1960	43.2	299	110	84	0.28

Source: Ethiopia Electric Power (EEP)

3.2.1. Classification of hydropower plants

Several LCA studies show that characteristics of hydropower plants such as installed capacities (sizes), water storage facilities (types) and their geographical location affect final results (Treyer and Bauer, 2016a; Zhang et al., 2007). Therefore, in LCA modelling, it is a common practice to classify hydropower plants mainly based on these characteristics. **Table 3.2** below depicts the classification of hydropower plants covered in this study. In terms of power generation capacity, they can be classified as micro-, small- and large-scale. According to Kadiyala et al. (2016), micro-hydropower plants typically refer to plants whose power generation capacities are below 0.1 MW, whereas small and large refer to between 0.1 - 30 MW and greater than 30 MW plants respectively. However, the size definitions of hydropower plants are flexible and vary from country to country based on local national policies (Elbatran et al., 2015; IPCC, 2011; Khan, 2015). For instance, in Sweden small-scale hydropower plants represent schemes with install capacity less than 1.5MW, Norway (≤10 MW), India (≤25 MW), Brazil (≤ 30 MW), Canada and China (≤50 MW) and between 5 and 100 MW in U.S (Elbatran et al., 2015). Tkáč (2018) has proposed size classification between values as Pico (<5 kW), micro (5 - 100 kW), mini (100 kW – 1 MW), small (1 - 25 MW), medium (25 - 100 MW) and large (100 - 500 MW) and very large (>500 MW). In Ethiopia, there is no official definition that classifies hydropower projects based on their capacities and thus different studies used different size classifications. Varun et al (Varun et al., 2010) classified Ethiopian hydropower plants 10 MW as divide-line for small and large hydropower plants, while Dametew (2016) categorized as small-scale (<40 MW), medium-scale (40 - 60 MW) and large-scale (>60 MW). For this study, however, Tkáč (2018) classification criteria have been applied where upper limit of power generation cappacies of small-sacle hydropower plants is 25 MW, medium-scale hydropower plants range between 25 - 100 MW and capacities of large hydropower plants are above 100 MW.

Based on water storage facilities, hydropower stations in Ethiopia are predominantly two types: Run-of-river and reservoir types. For the first look, Awash II, Awash III, Tis Abay II and Gilgel Gibe II can be considered as run-of-river hydropower plants with or without appreciable reservoir to store water behind dams. Awash II and Awash III have separate diversion weirs, pressurized tunnels and penstocks. Tis Ababy II plant has no diversion weir and rather uses unpressurized surface cannel that feeds water to the two pressurized penstocks connected to vertical Francis turbines. Gilgel Gibe II plant applies a 40 m high concrete weir for daily regulation (with capacity of 1.3 Mm^3) connected to 26 km concrete tunnel and 1.2 km two steel penstocks leading to powerhouse equipped with 4 pelton turbines. The Koka, Finchia, Melka Wakena, Gilgel Gibe I, Tekeze, Beles and Amerti-neshi receive their turbine water from reservoirs and thus they are reservoir hydropower plants. However, many of them are interconnected. For instance, Awash II and III are cascades of Koka plant located about 25 km and 28 km respectively downstream of Awash River which are linked to about 23.8 m high gravity dam of net volume about 1680 Mm^3. Tis Abay II is located on the Abay River about 35 km downstream of Lake Tana which is the natural reservoir for Beles plant, thus Tis Abay II and Beles are thus connected through Lake Tana.

Similarly, Gilgel Gibe II is cascaded from Gibe I which has a reservoir behind a rock-filled dam (ECRD) of net volume around 668 Mm^3. The intake of Gilgel Gibe II is located on the Gibe River about 2.5 km downstream of the Gilgle Gibe I outlet. Gilgel Gibe I and

Gilgel Gibe II are synchronized so that the daily rated outflow of Gilgel Gibe I reservoir is about 101.5 m^3/sec. In Ethiopia, those diversion type run-of-river hydropower plants are dependent somehow on the reservoir hydropower plants that sizes of hydropower plants are more important than water storage facilities for the classification of hydropower plants in Ethiopia. Awash II and III are modeled as cascaded from Koka hydropower plant and Gilgel Gibe II is cascaded from Gilgel Gibe II hydropower plant. Accordingly, hydropower plants in Ethiopia consist of medium- and large-scale hydropower plants. In the base year, medium and large-scale hydropower plants generated an average of 351 GWh and 7427.4 GWh respectively.

Table 3.2 Classification and types of hydropower plants under study

Power stations	Scale	Type	Remarks
Amerti-neshi	M	Reservoir	Uses rock-filed dam. Net reservoir volume =363Mm^3; Head=587m
Tis Abay II	M	Diversion	Uses canal to divert water from Abay River
Beles	L	Reservoir	Takes turbine water from Lake Tana
Gilgel Gibe I	L	Reservoir	Employs rock-filled dam. Net reservoir volume=668Mm^3 ; Head = 223m;
Gilgel Gibe II	L	Diversion	Cascaded from Gibe I using a mass concrete weir
Tekeze	L	Reservoir	Uses a concrete arch dam. Net reservoir volume =5343Mm^3; Head=155m
Melka Wakena	L	Reservoir	Uses rock-filled dam. Net reservoir volume =606Mm^3; Head=297m
Finicha	L	Reservoir	Uses rock-filled dam. Net reservoir volume =389Mm^3 ; Head=517m
Awash III	M	Diversion	Cascaded from Koka dam using a concrete diversion weir.
Awash II	M	Diversion	Cascaded from Koka using a concrete diversion weir.
Koka	M	Reservoir	Uses concrete gravity dam. net reservoir volume =1680Mm^3 ; Head=37m;

N.B: M= medium, L= Large

Another classification of hydropower plants is based on the locations of reservoirs tropical, non-tropical or alpine regions, because greenhouse gas emissions from reservoirs depend on climatic conditions (Treyer and Bauer, 2013). Although Ethiopia is found in the tropical zone, it has different climatic zone due to the difference in altitude; namely hot zone, temperate zone and cool zone (locally known as *kolla, woina dega,* and *dega* respectively). The hot zone consists of areas lower than 1500 meters above sea level; the temperate zone encompasses regions with altitude between 1500-2500 meters in elevation and the cool zone consists of areas where altitude is above 2500m.The cool zone is further divided into two subzones consisting of areas between 2500 - 3000 meters (known as *dega*) and areas above an elevation of 3000 meters (known as cold highlands or *wirch* zone). The local classifications as *kolla, woina dega, dega and wirch* can be interpreted as "tropical", "subtropical", "temperate" and "alpine" regions (Kenworthy, 1966; Fazzini et al., 2015). Based on the average elevations, Tekeze reservoir (about elevation of 1010m a.s.l) is in tropical climate, koka (EL 1592m a.s.l) and Gilgel Gibe I (1660m a.s.l) reservoirs are in subtropical climate, Melka Wakena reservoir (about 2327m a.s.l), Finicha reservoir (2225m a.s.l) and Amerti-neshi (2210m a.s.l) are in temperate climate.

3.3. Research method

LCA has been used to evaluate environmental impacts associated to hydropower generation in a holistic perspective. Regarding system configuration, the attributional type LCA models used allows describing all processes and associated environmental impacts attributed to analyzed hydropower stations. The input and output flows of identified processes are the basis of data collection. More information can be found about attributional LCI modeling in (Curran et al., 2005; Ekvall and Weidema, 2004; Finnveden et al., 2009) and process-based LCI compilation in (C. T. Hendrickson et al., 1997; Majeau-Bettez et al., 2011). The structure and format of 'allocation, default unit' system provided by SimaPro LCA software is employed to link unit processes related to the analyzed system. In addition, the paper is organized following the principles and basic structure of ISO Standard 14040 LCA framework which comprises of four essential phases: namely goal and scope definition, life cycle inventory (LCI), impact assessment (LCIA) and interpretation. A sensitivity analysis is conducted as part of the interpretation phase.

3.3.1. Goal and scope definition

This paper presents average environmental impacts of hydropower generation systems in Ethiopia. The main objective of the study is to estimate the average environmental impacts of existing 11 hydropower schemes developed since 1960s that constitutes about the 96% of electricity to central grid. The intended aim is to contribute for availability of LCI and LCA data for Ethiopian electricity which may be used to perform LCAs of other economically significant products in Ethiopia. The expected target users include academia, LCA practitioners, facility operators and policy makers in the energy sector.

3.3.1.1. System, function and functional unit

The studied hydropower plants consist of diversion weirs or dams, pressure headrace pipes, penstocks, powerhouses and tailraces with exception that Tis Abay II has concrete canal connected to penstocks, pressure pipes and a powerhouse. Electricity generation is considered as mere function of all schemes although some dams (e.g., Koka, Finchia, Amerti-neshi dams) are multipurpose type providing water to irrigation fields downstream. For this study, the functional unit is generation of 1 MWh of electricity.

3.3.1.2. System boundaries and cut-offs

Defining system boundaries involves identifying life cycles and processes involved in the analyzed system. It is also used to specify the spatial and temporal aspects of these processes. Regarding to life cycle stages, this study considers raw materials extraction and processing, manufacturing of components and equipment, construction and operation and maintenance of hydropower plants and end-of-life waste management. The construction stage of hydropower plant includes building works like dams, waterways and powerhouses and installation of equipment such as generators, turbines, transformers and switchgear devices like breakers and different switches. Most of components and equipment as well as reinforcing and structural steels were manufactured outside Ethiopia. Data about material compositions and weights of these components and equipment were taken from technical drawings and specifications. The transportation stage involves the transport of equipment and construction materials to the plant sites. As stated above, all equipment and the construction materials such as structural and reinforcing steels were purchased and transported from abroad. Sea and road mode of transports were calculated using online distance calculators. It is assumed that cement is purchased directly from local industries, while sand and gravels were produced from local quarries and water from local water sources which are about 5km from the plant site.

In the operation and maintenance stage, unlike conventional fossil fuel power plants, no direct combustion emissions are derived from hydro-turbine operation. Therefore, the environmental impacts of this stage are mainly associated with the upstream production and manufacturing of materials for repair and replacement. Although studies suggest 30-40 years for mechanical and electrical parts (Flury and Frischknecht, 2012), during site visit, it is noticed that most structures, machines and equipment are operational for the last 40-50 years with limited replacement of components and only few complete replacements. For instance, records in power stations show that one transformer at Koka and one turbine at Walkena plants were fully replaced due to fire accident. In this study, 100% replacement rates of electro-mechanical, hydro-mechanical, power transformers and switchgear equipment are assumed in 100 years of service. In addition, some amount of greenhouse gases are emitted to the atmosphere from reservoirs, which depends on the age and location of the reservoirs as well as the biomass covered by and entering into the reservoirs (Barros et al., 2011; Hertwich, 2013; Louis et al., 2013). As discussed in section 2.1, Ethiopia exhibits all climatic conditions: hot, cold and very cold conditions. Existing Ethiopian hydropower reservoirs are predominantly situated in subtropical and temperate areas. Due to unavailability of local data, the average global hydropower reservoirs emissions of 85 gCO_2/kWh and 3 gCH_4/kWh are used in this study (Hertwich, 2013). GHG emissions in SimaPro for non-alpine and tropical regions are low compared to recent literature values (Barros et al., 2011; Deemer et al., 2016; Hertwich, 2013). The self-supplied internal electricity consumption was subtracted from the total electricity generated and the average annual net output is used in LCI and LCA models.

In the waste management phase, it is assumed that metal scraps generated during maintenance and rehabilitation of hydro-mechanical structures, generators, transformers, switchgear devices (e.g., breakers) and different cranes. At end of design period, it is assumed that all civil structures including dams and waterway structures (e.g., pipes and gates) will remain in place because it is recognized that removal of these structures could cause major environmental impacts than the construction itself (Bryan Karney et al., 2007; Zhang et al., 2007; Ribeiro and da Silva, 2010). In this study, it is assumed that 90 % of equipment materials would be recycled; polymers and plastics are incinerated; and porcelain and reinforced glasses are sent to the nearby landfill for disposal based on assumption in wind projects (Martínez et al., 2009; Venås, 2015).

Spatial boundaries: From inputs perspective, the system boundary of this study can be considered global. With the exception of locally produced construction materials (e.g., cement and aggregate), most components and materials inputs of the analyzed hydropower schemes were imported, mainly from Europe and China. **Figure 3.1** show that the foreground system covers transportation of equipment and materials, the construction and operation and maintenance processes are in Ethiopia that may justify the need for this study.

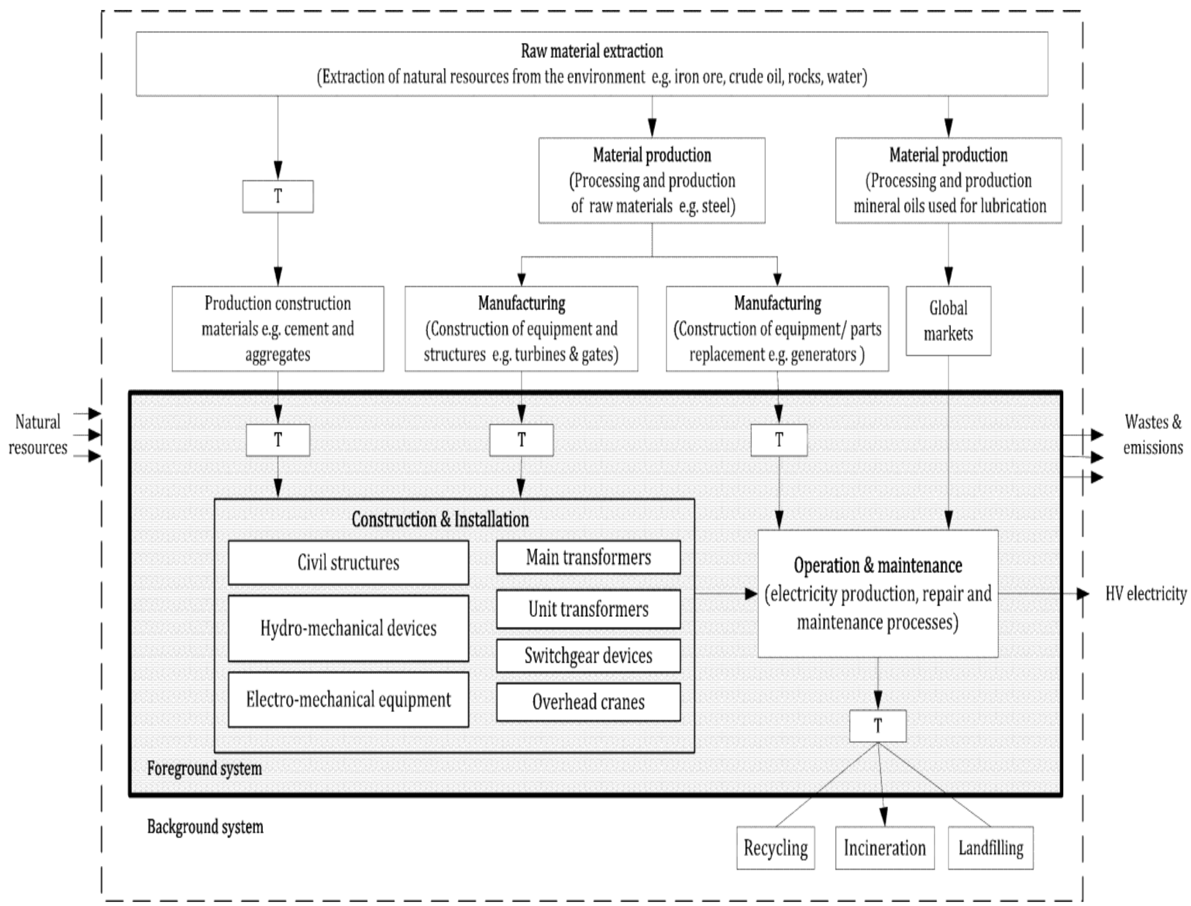


Figure 3.1 System boundaries for the life cycle assessment (LCA) of hydropower plants

Temporal boundaries: In terms of temporal boundaries, the analysis is divided in four phases: transportation, construction and installation, operation and maintenance and waste management. The construction phase included building of civil works and placing mechanical and electrical equipment. Regarding life time of hydropower plants there are different assumptions. In order to define a time boundary for LCI purposes, Varun et al. (2010) considered 30 years lifetime for canal-based run-of-river hydropower plant in India. Zhang et al. (2007) assumed a lifespan of 50 years for 44MW capacity reservoir hydropower plant connected to a rock-filled dam and 100 years for a reservoir hydropower plant (3600 MW) with concrete gravity dam. Wang et al. (2019) also used a lifespan of 50 years for 252 MW hydropower in China, but their system boundary did not show that maintenance and replacement of components have been modeled during the operation phase. On other hand, Flury and Frischknecht (Flury and Frischknecht, 2012) established a time horizons of 80 and 150 years for run-of-river and reservoir hydropower plants respectively. For this study a lifespan of 100 years was considered for all hydropower plants, which assumes complete replacement of a power plant through reinvestments. The baseline time period for data collection was between 2013 and 2017 to calculate average realized electricity generation and consumption of mineral oils. The analysis considered a 100-year time horizon for global warming potentials (GWP).

3.3.1.3. Allocation

Although some of dams of analyzed hydropower generation systems known to provide additional services such as fishing, irrigation and water supply, the no allocation procedure was used. Thus, the present study allocated all impacts of hydro power projects to the electricity generation function which is a conservative consideration.

3.3.2. Life cycle Inventory

3.3.2.1. Data types and sources

In LCA studies, data collection is the most laborious and time-consuming activity because huge amounts of LCI data are required for describing a given real system. In this study, LCI data collection process followed three consecutive steps: the first step is identification of structures, equipment and processes used during the construction, transportation, operation and waste disposal phases of the analyzed system. The second step is collection of data and information on amount resource consumption and emissions associated to these components and processes. The last step is about estimating the life cycle burdens of each input materials using Ecoinvent database version 3.01.

As shown in **Table 3.3** below, technical drawings and specifications of machines and equipment, commissioning reports and local database of Ethiopian Electric Power (EEP) were sources of most primary data for calculating the type and amount of material used in the manufacturing of different components and construction of the hydropower plants. Complementary information is obtained from site visits of all hydropower plants and personal communications with the staff in charge of the hydropower operation. Energy consumption during manufacturing and construction phases was obtained from secondary sources mainly sectoral reports and published article.

Table 3.3 LCI data types and their sources

Life cycle stage	Data collected	Data source
Construction	Types and weights of materials used to construct civil works such as dams, waterways and powerhouses; as well as hydraulics, mechanical and electrical structures and equipment like gates, penstocks, turbines, generators and overhead cranes	Technical drawings and specifications, commissioning reports, site observations and personal communications
	Types and weights of materials for transformers and switchgear devices like circuit breakers, current transformers, voltage transformers, disconnecting switches and lightning arrestors	Supplier technical drawings and specifications and (ABB, 2003; Wang et al., 2011)
	Data on clinker and cement production	Local cement industries
	LCI dataset for material inputs for the manufacturing of civil structures and hydro- and electro-mechanical equipment such as aggregates and steel	Ecoinvent database version 3.01 in SimaPro software version 8.0.3.14
	Fuel and electricity consumption	Published articles (Flury and Frischknecht, 2012; Varun et al., 2010; Zhang et al., 2007) and report
	Concrete mix design	Published article Dinku et al.(2002)
	Emission factors for fuel combustion	IPCC (Gagnon and Van De Vate, 1997)
Transportation	Suppliers information	Nameplates, drawings and contract documents
	Distance of different transport modes	Online calculators: https://sea-distances.org/
Operation and maintenance	Daily electricity production	EEP information desk
	Oil consumption	Bin cards in plants sites
	Land requirements	Feasibility and EIA reports
	Fuel and electricity	EEP information disk
End of life stage	LCI datasets for metal scraps and other waste like plastics and glasses)	Ecoinvent 3.01database in SimaPro software version 8.0.3.14.

3.3.2.2. Inventory analysis results

For data and parameters in Table 3.3 above, the calculated life cycle inventory results for 1MW electricity production from medium (25-100MW) and large (≥100MW) capacity hydropower plants are presented in **Table 3.4** below. The total consumption for cement to construct medium and large-scale hydropower plants was 5.08 and 1.08 kg respectively. Iron and steel are other important material inputs during construction and maintenance phases. In the operation and maintenance phase, products made of iron and steel are used to repair and/or replace components and parts. The life cycle consumption for reinforcing steel, low-alloyed steel, cast iron and chromium steel of medium-scale hydropower plants were 0.63, 0.19, $6.51*10^{-4}$ and, $7.65*10^{-3}$ kg per 1MWh electricity produced respectively. The corresponding values for large plants were 0.16, 0.17, $4.31*10^{-4}$ and, $1.89*10^{-3}$ respectively. The result shows that the medium scale hydropower plants have higher material and energy uses than large-scale ones per unit electricity production.

3.3.3. Impact Assessment

In this stage of LCA, the results of inventory analysis are transformed to environmental impacts based on certain characterization models (ISO, 2006a). There are several characterization methods used in LCA studies, including the CML 2001, IMPACT 2002+, ReCiPe 2008, and ILCD 2009 methods (EC-JRC, 2010; Finnveden et al., 2009; Goedkoop et al., 2008; Park et al., 2014; Rosenbaum, 2017; Weidema, 2015). The selection of one method from others is not always clear. It could be affected by area of study and impact categories considered (Amani and Schiefer, 2011), user's experience (Chevalier and Tatiana Reyes-Carrillo, 2011) and the availability of previous works for comparison of results (Finnveden et al., 2009). The ReCiPe 2008 method has been used by previous researchers (Briones Hidrovo et al., 2017a), which allows comparison of results of LCA studies. In addition, ReCiPe 2008 provides environmental information on 18 category indicators as shown in **Table 3.5** below. Therefore, the need to compare our results with previous studies and to provide information on relatively large number of impact indicators, ReCiPe 2008 impact assessment method was applied in this study.

Table 3.4 LCI data of hydropower plants in Ethiopia (per kWh)

Materials	Unit	Medium hydropower plants		Large hydropower plants	
		Construction	Operation and Maintenance	Construction	Operation and Maintenance
Aluminum	g	2.71E-04	2.71E-04	1.05E-04	8.99E-05
Brass	g			7.48E-07	7.48E-07
Bronze	g			3.04E-06	3.04E-06
Cast iron	g	6.41E-04	1.01E-05	2.46E-04	1.85E-04
Chromium steel	g	3.83E-03	3.83E-03	1.01E-03	8.78E-04
Copper	g	3.77E-03	3.77E-03	1.67E-03	1.67E-03
Glass fiber	g	5.47E-05	5.47E-05	2.18E-05	2.18E-05
Insulations	g	5.30E-04	5.30E-04	2.05E-04	2.05E-04
Paint	g	2.88E-05	2.88E-05	1.04E-05	1.04E-05
Polymers	g	4.20E-06	4.20E-06	1.95E-06	1.95E-06
Porcelain	g	1.46E-03	1.20E-03	3.58E-04	3.58E-04
Resin	g	1.17E-05	1.17E-05	1.21E-04	1.21E-04
Rubber	g	7.20E-05	7.20E-05	8.61E-06	8.61E-06
SF6	g	4.07E-06	4.07E-06	1.76E-06	1.76E-06
Low alloyed steel	g	1.25E-01	6.93E-02	1.05E-01	6.00E-02
Water	g	3.27E+00	3.74E-01	7.89E-01	1.53E-01
Wood	m3	4.18E-04	4.18E-07	1.20E-07	1.20E-07
Zinc coating	g	1.79E-05	1.79E-05	5.75E-06	5.75E-06
Cement	g	5.08E+00		1.04E+00	
Gravel	g	1.98E+01		4.01E+00	
Sand	g	1.07E+01		2.54E+00	
Reinforcing steel	g	6.29E-01		1.55E-01	
Bentonite	g	5.16E-04		5.86E-03	
Basalt	g	7.62E-02		7.23E-03	
Mineral oils	g		1.03E-02		3.57E-03
Energy use	MJ	1.48E+01		1.91E-03	2.88E-03
Electricity, medium	KWh	9.48E+00		3.61E03	5.01E-02
Road transport	tkm	1.82E-01	1.73E-04	1.03E-04	1.02E-04
Sea transport	tkm	6.40E-01	1.07E03	4.80E-04	4.75E-04

3.3.4. Limitations and assumptions

The LCI process does not cover direct ecological and social impacts of hydropower plants such as land loss, dislocation of settlers, possible ecosystem modifications and risk of failures for which many design procedures and impact assessment studies and methodologies are available. Other main assumptions and limitations include:

- The lifetime of 100 years is assumed both for run-of-river and reservoir-based hydropower plants. The effect of lifetime choice on the final LCA results is discussed in the sensitivity analysis section.
- The 5-year average energy production of each power plant was used to calculate impacts which could be affected by climate variations.
- Norwegian electricity mix dataset was used to model the electricity consumption during construction phase and during cement production in local cement industries considering the fact that both Norwegian and Ethiopian grids are dominated by hydroelectricity.

3.4. Results and discussion

3.4.1. Overall environmental impacts

Table 3.5 presents the total average potential environmental impacts of eleven operating hydropower plants using the method ReCiPe 2008 midpoint (H) V1.10/world recipe H. These impact indicators were calculated per 1kWh of electricity generated and supplied to the central grid. When medium-and large scale hydropower plants are considered as two different groups, the average value of each environmental impact factor from medium plants is higher than its counterpart from large-scale ones, which is consistent with results of (Zhang et al., 2007) that reported the impacts of 44MW hydro plants is larger than

3600MW. However, in the production mix at system level, the contribution of medium-scale hydropower plants is lower than large plants with the exception of natural land transformation because Koka and Amerti-neshi power plants use extended land for reservoirs (see **Table 3.6**). At system level, the construction phase contributes the largest share in most impact categories (58 - 95%) except that the operation and maintenance phase contribute nearly 79, 91, 98 and 100% of urban land occupation, climate change, water depletion and natural land transformation contribution respectively. The contribution of transportation swings between 1 and 2%. The recycling of metal scraps during end-of-life waste disposal would reduce freshwater eutrophication and metal depletion by 55 and 22 %. In the following subsections, a detail contribution analysis is carried out for some impact categories.

Table 3.5 LCIA results of hydropower plants in Ethiopia per 1 kWh electricity generation

Impact category	Unit	LCIA results (per kWh)	
		Medium HPPs	Large HPPs
Climate change (CC)	g CO2 eq	6.26E+01	3.07E+01
Ozone depletion (OD)	g CFC-11 eq	5.75E-07	1.32E-07
Terrestrial acidification (TA)	g SO2 eq	8.22E-02	1.54E-02
Freshwater eutrophication (FEU)	g P eq	4.81E-04	1.15E-04
Marine eutrophication (MEU)	g N eq	3.35E-03	5.65E-04
Human toxicity (HT)	g 1,4-DCB eq	1.59E+00	5.37E-01
Photochemical oxidant formation (POF)	g NMVOC eq.	1.22E-01	2.85E-02
Particulate matter formation (PMF)	g PM10 eq	8.52E-01	1.15E-01
Terrestrial ecotoxicity (TE)	g 1,4-DCB eq	6.87E-04	2.48E-04
Freshwater ecotoxicity (FE)	g 1,4-DCB eq	3.10E-03	9.19E-04
Marine ecotoxicity (ME)	g 1,4-DCB eq	1.75E-02	5.92E-03
Ionizing radiation (IR)	Bq U235 eq	4.73E-01	9.68E-02
Agricultural land occupation (ALO)	m^2a	1.76E-04	3.80E-05
Urban land occupation (ULO)	m^2a	4.65E-04	1.96E-04
Natural land transformation (NLT)	m^2	3.79E-03	6.88E-04
Water depletion (WD)	m^3	2.99E+00	1.45E+00
Metal depletion (MD)	g Fe eq	2.68E+00	9.65E-01
Fossil depletion (FD)	g oil eq	3.41E+00	6.97E-01

Note: HPPs = hydropower plants

Table 3.6 Contribution of medium and large scale HPPs to total impacts (per 1kWh)

Impact category	Unit	LCIA results (per kWh)		
		Production	Medium HPPs	Large HPPs
Climate change (CC)	g CO2 eq	3.21E+01	2.83E+00	2.93E+01
Ozone depletion (OD)	g CFC-11 eq	1.52E-07	2.61E-08	1.26E-07
Terrestrial acidification (TA)	g SO2 eq	1.84E-02	3.72E-03	1.47E-02
Freshwater eutrophication (FEU)	g P eq	1.32E-04	2.18E-05	1.10E-04
Marine eutrophication (MEU)	g N eq	6.91E-04	1.52E-04	5.40E-04
Human toxicity (HT)	g 1,4-DCB eq	5.84E-01	7.18E-02	5.13E-01
Photochemical oxidant formation	g NMVOC eq	3.27E-02	5.53E-03	2.72E-02
Particulate matter formation (PMF)	g PM10 eq	1.49E-01	3.86E-02	1.10E-01
Terrestrial ecotoxicity (TE)	g 1,4-DCB eq	2.68E-04	3.11E-05	2.37E-04
Freshwater ecotoxicity (FE)	g 1,4-DCB eq	1.02E-03	1.40E-04	8.77E-04
Marine ecotoxicity (ME)	g 1,4-DCB eq	6.45E-03	7.94E-04	5.65E-03
Ionizing radiation (IR)	Bq U235 eq	1.14E-01	2.14E-02	9.24E-02
Agricultural land occupation (ALO)	m^2a	4.42E-05	7.96E-06	3.62E-05
Urban land occupation (ULO)	m^2a	2.09E-04	2.11E-05	1.88E-04
Natural land transformation (NLT)	m^2	8.28E-04	1.72E-04	6.57E-04
Water depletion (WD)	m^3	1.52E+00	1.36E-01	1.39E+00
Metal depletion (MD)	g Fe eq	1.04E+00	1.22E-01	9.21E-01
Fossil depletion (FD)	g oil eq	8.20E-01	1.55E-01	6.66E-01

Note: HPPs = hydropower plants

Based on normalization of the impact indicator results, the numbers of impact categories selected for discussion and contribution analysis are narrowed to ten as shown in **Figure 3.2** and **3.3** below for medium-and large-scale hydropower plants.

3.4.2. Contribution analysis

3.4.2.1. Climate change (CC)

As shown in **Table 3.5** above, the life cycle GHG intensities on a per kWh electricity generated are 64 and 31 g CO_2-eq medium and large hydropower plants respectively. In medium plants; construction, operation and maintenance, transportation and waste management phases account for 14, 85, 0.2 and 0.7 % of the total GHG emission respectively. The corresponding values for large plants are 9, 91, 0.2 and -0.02 % of the total GHG emission respectively. The negative sign indicates the reduction of GHG emission due to recycling of metal scraps. The operation and maintenance phase constitutes the largest share of the GHG emissions both in medium and large-scale hydropower plants since because of extra GHG emissions from reservoirs. It is important considering that this indicator is extremely sensitive to the selection of GHG (especially CH_4) for the hydropower reservoirs.

3.4.2.2. Human toxicity (HT)

The human toxicity is used as an indicator of impacts on human health due to substances in soil, water and air attributed to analyzed system. In this study, the human toxicity values of medium and large-scale hydropower plants are 1.6 and 0.54 g 1,4-DCB eq. per MWh respectively (i.e., system total 0.58 g 1,4-DCB eq.). The construction, operation and maintenance, transportation and waste disposal phases account for 63, 36, 0.22 and -2.2% for medium hydropower plants. The corresponding values for large-scale schemes are 69, 31, 0.3 and -3.5 % respectively. The contribution of operation and maintenance phase to human toxicity is nearly zero. For the system as whole, the contribution analysis showed that copper production (45%), steel production (37%) and energy use (10%) is the predominant contributor of the impact indicator. In terms of substances, the arsenic, mercury, lead and cadmium emissions to air related to copper production comprise about 86% of the total impacts. The contribution analysis shows that large-scale hydropower plants are the highest contributor of the total impacts (63%).

3.4.2.3. Terrestrial acidification (TA)

The main contributions to acidification impact are from the construction of hydropower plants (79%) followed by the operation and maintenance phase (18%). The processes like diesel combustion (both in building machines and transportation vesicles), electricity generation, steel production, copper production and clinker production contribute about 21, 30, 30, 7 and 7 % of the total impact respectively. The contribution of transportation for TA is just less than 4%. The major acidifying substances are sulfur dioxide (53%) and nitrogen oxides (46%). The contribution of ammonia and other sulfur oxides are negligible.

3.4.2.4. Freshwater eutrophication (FEU)

The construction and operation and maintenance phase account about 62% and 38% respectively. Credits from recycling of steel, aluminum and copper scraps reduce the overall impact by 59%. The main contributing processes of FEU are copper production (50%), steel production (34%) and waste landfilling (12%). The main contributing substance to the FEU is phosphate in water (98%) emitted from the above processes.

3.4.2.5. Metal depletion (MD)

Metal is an important input for the manufacturing of components and equipment (e.g., gates, turbines, generators and transformers) that are used to construct and rehabilitate hydropower plants. The total steel consumptions of medium and large-scale hydropower plants were 2.7 and 0.96 g Fe eq./kWh respectively while the total average system steel use is about 1.04 g Fe eq./kWh. The contribution analysis showed that the construction, operation and maintenance, transportation and waste disposal phases comprise about 75, 25, 0.13 and -20 % and 76, 24, 0.2 and -22 % respectively of total impacts of medium and large-scale hydropower plants. For the total system, production of steel and copper constitute about 82 and 15 % of the total metal depletion. The analysis also revealed that the production of secondary materials through recycling of metal scraps could bring about 22 % reductions for primary steels. In terms of metallic composition, the extraction of iron, manganese, nickel, chromium tin and copper from the natural environment comprise about 32, 30, 20, 14 and 2.6% respectively.

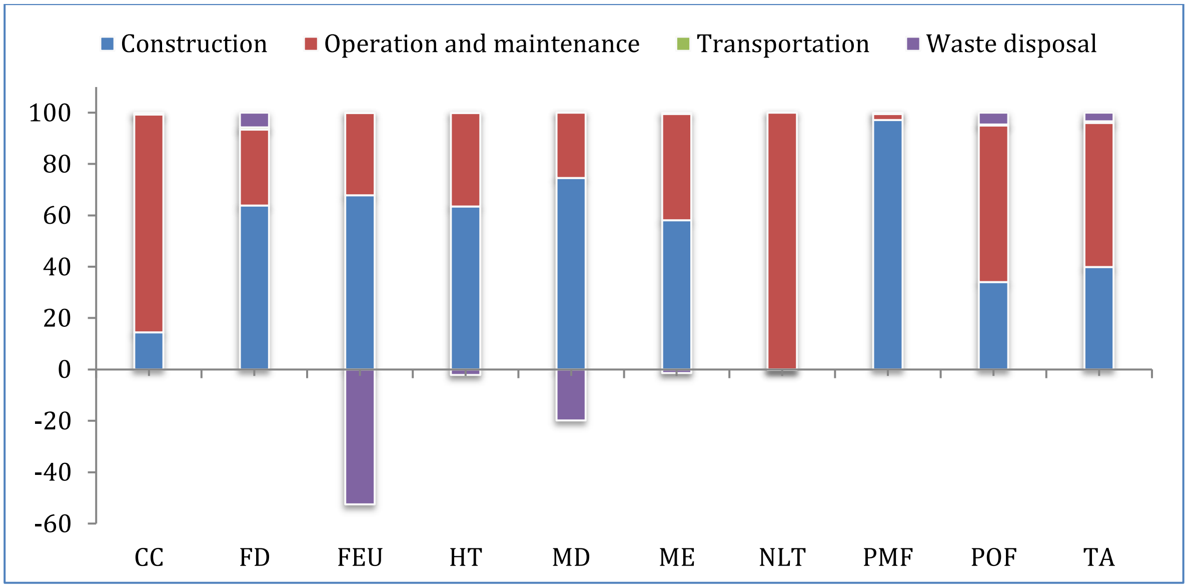


Figure 3.2 Processes contribution for selected impact indicators of medium-scale hydropower plants

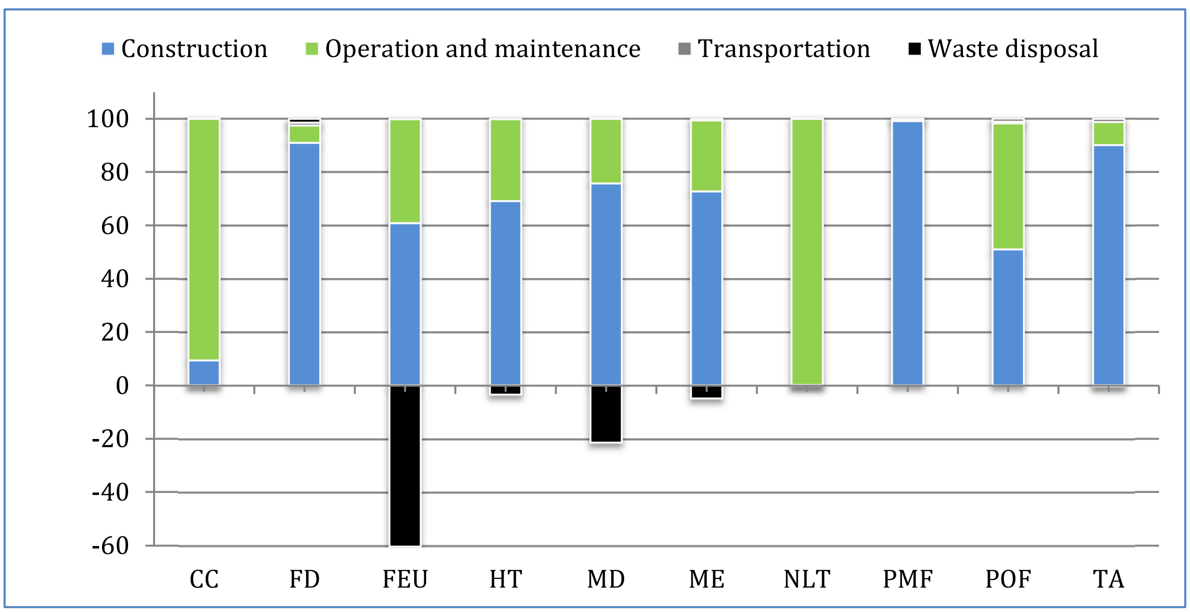


Figure 3.3 Processes contribution for selected impact indicators of large-scale hydropower plants

CC = Climate change, FD= Fossil depletion, FEU=Freshwater eutrophication, HT= Human toxicity, MD=Metal depletion, ME= Marine ecotoxicity, NLT= Natural land transformation, PMF= Particulate matter formation, POF= Photochemical oxidant formation, TA=Terrestrial acidification.

3.4.2.6. Other impact categories

Figure 3.2 and **3.3** also show the contribution of LC stages in impact categories of photochemical oxidant formation (POF), particulate matter formation (PMF), marine ecotoxicity (ME) and natural land transformation (NLT). The pattern is the same; the average impacts of medium-scale hydropower plants are larger than large ones. The construction of medium and large power plants account for approximately 97-99, 34-50 and 57-72 % respectively of total impacts of PMF, POF, and ME, with exception that operation and maintenance phase contribute more than 99% of NLT.

3.4.3. Comparison with previous hydropower plant studies

Comparison of LCA results with results of previous studies is considered useful to substantiate results at the level of electricity generation technologies (Santoyo-Castelazo et al., 2011). However, studies (IPCC, 2011; Wanga et al., 2019) suggest that comparing of LCA results is complex since many factors trigger differences between LCA studies including the choice of lifespan, installed capacities, type (run-of-river (RoR) or reservoir), energy production used to calculate results (expected or actual), system boundaries, methane emissions from underwater decomposition and electricity mix (Masanet et al., 2013; Weisser, 2007). For his study, impact indicators of climate change and fossil depletion are selected for comparison, because GHG emissions and energy use are most frequently evaluated parameters in energy generation systems. As shown in Table 5, the overall system GHG emission intensity obtained in this study is about 32 g CO_2 eq./kWh, which is in the range reported by several case and survey studies for hydropower generation systems (i.e., 1 to 44 g CO_2 eq./kWh). However, the GHG emission of medium hydropower plants is higher than the value reported by (Zhang et al., 2007) for 44 MW hydropower plant in China. One reason for this difference may be type of dams used in these two hydro plant systems. Most medium-scale plants analyzed this study use gravity dams and mass concrete diversion weirs; where as in the later analyzed a rock-filled dam type possibly with less amount of concrete.

The natural fossil depletion potential for this this study range between approximately 0.7-3.41 g oil eq./kWh (overall system average is 0.82 g oil eq./kWh), which is between the lower range of other studies (0.88 - 103 g oil eq./kWh) shown in **Table 3.7** below. The electricity mix could be considered as main factors affecting energy use indicators. In this study, the electricity input during construction phase was assumed from a grid connected predominantly (more than 90%) renewable technologies. On other hand, the electricity consumptions during manufacturing of construction materials and equipment were assumed from grids of country of suppliers.

Table 3.7 Comprsion of GHG emission intensities and energy use with previous studies

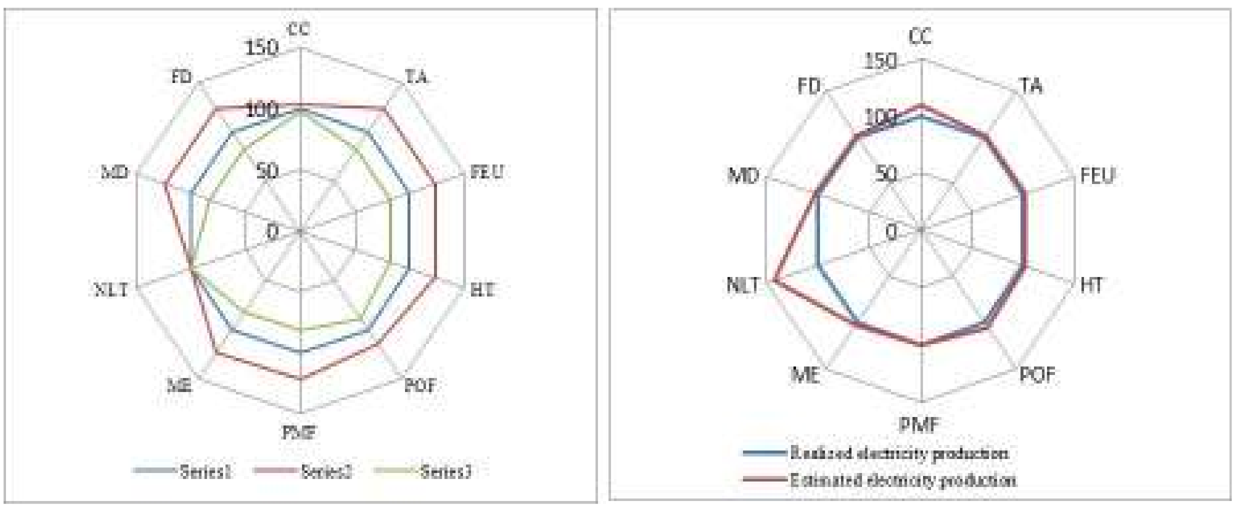
Reference	Study type	Capacity (MW)	Category	Life span (years)	g CO_2-eq./kwh	g oil-eq./kWh
This study	Case	Several	Mixed	100	32.14	0.82
		Several	Mixed, M	100	62.6	3.41
		Several	Mixed, L	100	30.7	0.7
Zhang et al.(2007)	Case	44	R - M	50	44.00	11.56
		3600	R - VL	100	6.00	1.77
Varun et al. (2010)	Case	30	RoR - L	30	11.90	2.28
Flury and Frischknecht (2012)	Case	95	R - M	150	10.80	102.72
Briones Hidrovo et al. (2017a)	Case	42	R - M	100	5.77	0.88
Kabayo et al. (2019)	Case	96	R - M	150	14.00	
Atilgan and Azapagic (2016)	Case	Several	Mixed	150	8.30	
Vattenfall Vattenkraft AB (2015)	Case	Several	Mixed	100	8.60	
IPCC (2011)	Survey	Several	Mixed	n/a	4 - 14	
Kadiyala et al. (2016)	Survey	Several	R - L	n/a	40.60	
Weisser (2007)	Survey	Several	Mixed	n/a	1-34	

N.B. RoR= run of river; R= reservoir; M=medium; L= large; VL = very large

3.5. Sensitivity analysis

Lifetime and annual electricity output are two key factors for the calculation of specific environmental burdens from energy generation systems. As we can see in table 7 above, different LCA studies considered different lifespans for large hydropower plants ranging from 80 to 150 years. This difference in lifespan affects the life cycle electricity production and thus the LCA results. **Figure 3.4** below presents the results of sensitivity analysis for lifespan and electricity production. The baselines are a lifespan of 100 years and life cycle electricity calculated based on average realized annual electricity production. As shown in figure 4 below, reducing the lifespan of hydropower plant systems by 20 years would result in an increase in all impact categories. For instance, climate change increases by 3 % and others indicators except natural land transformation indicators increase by 21-24%.

On other hand, increasing of lifespan by 20 years would reduce climate change (CC) by 2 % and most other impact indicators decrease by 17-18 %. Furthermore, when the expected annual electricity generation was used as basis of analysis, the sensitivity analysis shows a 2 % increase in most impact indicators, where climate change, Photochemical oxidant formation and natural land transformation decrease by 9, 5 and 43 % respectively. The reduction in all impact categories implies the life cycle electricity production calculated based on average realized annual electricity generation would have less overall environmental impacts than based on expected or designed annual electricity generation, which is encouraging. It is also worth mentioning that the climate change impact of a hydropower plant is very sensitive to the GHG emissions of its reservoir, especially for CH_4 emission. The GHG emissions in turn depend on the location of the reservoir. The CO_2 emissions of reservoirs in temperate areas are 74 and 211 g per kWh and the CH_4 emissions for reservoirs in tropical areas are 1.3 and 8.1 kWh per kWh (Hertwich, 2013). For analyzed hydropower plants, Tekeze reservoir is located in tropical climate and other reservoirs situated in subtropical and temperate zones (Fazzini et al., 2015; Kenworthy, 1966). In this study, the global average GHG emissions of hydro-reservoirs were used as baseline scenario. The total climate change potential is about 36 g CO_2 eq./kWh when hydropower plants are modeled using tropical GHG emissions for Tekeze hydropower plant and temperate emissions for other hydropower plants, which is 12 % larger than the baseline result.



a) Effects of lifespan on final LCA results (b) Effects of electricity production on final LCA results

Figure 3.4 Depicts Effects of life span and electricity production on final LCA results

CC = Climate change, TA=Terrestrial acidification, FEU=Freshwater eutrophication, HT= Human toxicity, POF= Photochemical oxidant formation, PMF= Particulate matter formation, ME= Marine ecotoxicity, NLT= Natural land transformation, MD=Metal depletion, FD= Fossil depletion

In addition, in order to provide information to users on influence of recycling on the final result, scenario analysis has been conducted at different recycling rates (**Table 3.8** below).

Table 3.8 Sensitivity analysis of recycling rates on the LCA results of hydropower system

Rates (%)	CC (g CO2 eq.)	FD (g oil eq.)	FEU (g P eq.)	HT (g 1,4-DB eq.	MD (g Fe eq.)	ME (g 1,4-DB eq.)	NLT (m2)	PMF (g PM10 eq.)	POF (g NMVOC eq.)	TA (g SO2 eq.)
0	32.240	0.841	0.0003	0.608	1.331	0.007	0.001	0.149	0.033	0.019
20	32.217	0.836	0.0002	0.602	1.249	0.007	0.001	0.149	0.033	0.019
40	32.197	0.832	0.0002	0.598	1.203	0.007	0.001	0.149	0.033	0.019
60	32.175	0.828	0.0002	0.592	1.138	0.007	0.001	0.149	0.033	0.019
80	32.153	0.823	0.0002	0.588	1.076	0.007	0.001	0.149	0.033	0.018
90	32.140	0.820	0.0001	0.584	1.042	0.006	0.001	0.149	0.033	0.018

The analyzed system is credited for amount of secondary materials produced above the recycled contents (of steel, copper and aluminum) in the production phase for the possible reduction of environmental impacts resulting from the reduced demand for primary material from nature (Nakatani 2014; Frischknecht 2010). According to SimpaPro software version 8.0.3.14, the recycled contents of steel, copper and aluminum are about 37, 34.7 and 39% respectively. Table 8 presents the sensitivity analysis results of recycling rates starting from zero recycling rates to 90% recycling rate. The recycling of steel scraps generally results in reduction in most impact categories. For instance, the GHG emissions at recycling rates of 20 and 80% are about 32.22 and 32.15 g CO_2 eq. /kW. This corresponds to a 0.25 and 0.03% increase as compared to the impacts of the baseline scenario (i.e., 90% recycling rate), which is almost consistent to 0.06-0.28% saving for climate change (i.e., as reference to 0 % recycling rate).

3.6. Conclusion and recommendations

Life cycle assessment has been performed for hydropower system of Ethiopia that comprise of eleven hydropower plants that were operational in 2013-2017. The major overall mid-point environmental impacts of the analyzed hydropower system were global warming potential (32.14 g CO_2 eq./kWh), fossil depletion potential (0.82 g oil eq. /kWh), freshwater eutrophication potential (0.000132 kg P eq./kWh), human toxicity potential (0.58 g 1, 4-DCB eq./kWh), metal depletion potential (1.04 g Fe eq./kWh), marine ecotoxicity potential (0.01 g 1,4-DCB eq./kWh), natural land transformation potential (0.83 m^2), particulate matter formation potential (0.15 g PM10 eq./kWh), photochemical oxidant formation potential (0.033 g NMVOC eq./kWh) and terrestrial acidification potential (0.0184 g SO_2 eq./kWh). Moreover, medium hydropower plants have higher potential environmental impacts when compared with large-scale hydropower plants. In general, the construction of hydropower plants contributes the highest share (62-99%) in most impact indicators, with exception that operation and maintenance phase accounts for about 50 and 90 % share in photochemical oxidant formation and climate change. The results of sensitivity and scenario analyses showed that the LCA results would be affected by parameters such as life span and amount of electricity generated.

In general, this study would offer insight for developers and utility companies (operators) to pay proper attention during selection of installed capacities of hydropower plants, determination of plant sites and design periods, and prepare maintenance schedule to enhance production and reduce breakdowns. Moreover, the study could be used as input for the national energy system LCA studies by local researchers. The considerable effect of lifespan on final LCA results and the benefits from recycling of metals scraps indicates that organizations (developers and operators) should integrate LCA during the design processes to achieve environmental improvement in all life stages of the hydropower plants. Finally, here it is worth mentioning, however, that this study was conducted under certain limitations such as lack of local datasets for electricity, transport and waste treatment activities relevant to local conditions. Therefore, further study should be undertaken to strengthen the life cycle inventory assessments for such background systems in Ethiopia.

4. LIFE CYCLE ASSESSMENT OF ETHIOPIAN WIND FARMS

Abstract

The overall aim of this study is to contribute to the creation of LCA database on electricity generation systems in Ethiopia. This study specifically estimates the environmental impacts associated with wind power systems supplying high voltage electricity to the national grid. The study has regional significance as the Ethiopian electric system is already supplying electricity to Sudan and Djibouti, and envisioned to supply to other countries in the region.

Three different grid-connected wind power systems consisting of four different models of wind turbines with power rates between 1 MW and 1.67 MW were analyzed for the situation in Ethiopia. The assessment takes into account all the life cycle stages of the total system, cradle to grave, considering all the processes related to the wind farms: raw material acquisition, manufacturing of main components, transporting to the wind farm, construction, operation and maintenance, and the final dismantling and waste treatment. The study has been developed in line with the main principles of the ISO 14040 and ISO 14044 standard procedures. The analysis is done using SimaPro software 8.0.3.14 multi-user, Ecoinvent database version 3.01 and ReCiPe 2008 impact assessment method. The assumed operational lifetime as a baseline is 20 years.

The average midpoint environmental impact of Ethiopian wind power system per kWh electricity generated are for climate change: 33.6 g CO_2 eq., fossil depletion: 8 g oil eq., freshwater ecotoxicity: 0.023 g 1,4-DCB eq., freshwater eutrophication: 0.005 g N eq., human toxicity: 9.9 g 1,4-DCB eq., metal depletion: 18.7 g Fe eq., marine ecotoxicity: 0.098

g1,4-DCB eq., particulate matter formation: 0.097 g PM10 eq., photochemical oxidant formation: 0.144 g NMVOC eq., and terrestrial acidification: 0.21 g SO_2 eq. The pre-operation phase that includes the upstream life cycle stage is the largest contributor to all the environmental impacts, with shares ranging between 82% and 96%. The value of cumulative energy demand (CED) and energy return on investment (EROI) for the wind power system are 0.393 MJ and 9.2 respectively.

The pre-operation phase is the largest contributor to all the environmental impact categories. The sensitivity and scenario analyses indicate that changes in wind turbine lifespans, capacity factors, exchange rates for parts, transport routes and treatment activities would result in significant changes in the LCA results.

4.1. Introduction

The contribution of wind power in the electricity system is increasing as sustainability issues like climate change attract global attention and the search for alternative energy sources gains momentum. According to the International Renewable Energy Agency (IRENA), the total global installed capacity of wind power in 2019 was around 623 GW, which is an increase of 10.4% compared to 2018 (IRENA, 2019a). This figure is projected to reach 6044 GW in 2050 and account for about 36% of world energy demand (IRENA, 2019b). It is reported that in 2019 the wind power capacity in Africa was 5.8 GW, where Ethiopia with installed capacity of 324 MW energy from wind power is the fifth top African country next to South Africa, Morocco, Egypt and Kenya (IRENA 2020a). Africa's total renewable energy capacity in the same year was 48.4 GW. Ethiopia has a huge wind power potential estimated to be around 10 GW covering different regions of the country (Wudu, 2015). The Ministry of Water, Irrigation and Energy of Ethiopia (MoWIE) as part of its green development policy has planned to develop the country's wind power from current 324 MW to 2000 MW by the year 2030 (MoWIE 2012).

Wind power systems offer relatively low environmental impact renewable energy. However, studies point to direct and indirect environmental issues associated with such systems (e.g., Wang et al. 2015a). The local impacts of wind power include noise pollution and damages to birds' life (Kaldellis et al., 2012; Leung and Yang, 2012; Saidur et al., 2011; Wang et al., 2015b; Wang and Wang, 2015). In this study, relevant LCA case studies and reviews focusing on wind power systems are discussed and used to compare and benchmark the results of this study. The criteria used for selecting relevant studies include the type and capacity of wind turbines, lifespans, scope of LCA impact categories, and methods applied. For example, Abeliotis & Pactiti (2014), Navarro-Pineda et al. (2017), Iberdrola (2018), Ozoemena et al. (2018), Xu et al. (2018) and Wanga et al. (2019) performed process-based LCA with a wide range of indicators relevant to our study. Asdrubali et al. (2015) reviewed and summarized the LCA results of wind power systems. Kubiszewski et al. (2010) and Walmsley et al. (2018) evaluated the energy return on investment (EROI) of wind power systems. Other studies evaluated the effects of lifespans (D'Souza et al., 2011; Vestas, 2015), capacity factors (Boccard, 2009), metal scrap recycling rates (Haapala and Prempreeda, 2014a; Wanga et al., 2019) and replacement rates of parts (Vestas, 2015) on the LCA results of wind power. Most of the LCA studies are, however, limited to the circumstances of China, Europe, and North America with only few LCA studies of wind farms focusing on Africa (Al-Behadili and El-Osta, 2015).

The core of Ethiopian development strategies (FDRE, 2011b) and plans (National Planning Commission, 2016) aims at the development of energy systems with low carbon energy sources, including wind power although the country's global emission share is still very low. The national electric power system is supplying electricity to Sudan and Djibouti, and is envisioned to supply to other countries in the region such as Kenya (Wudu 2015, DANIDA 2016). While the intention to develop low carbon energy sources to further reduce the environmental impact of the country is commendable, the overall environmental impact associated with its wind power system is not researched yet. The absence of studies is also true for other energy and non-energy product systems as only few LCA studies were conducted in Ethiopia, in part due to lack of data. For instance, Bekele (2007) conducted an LCA of glove leather production at Ethio-leather industry in Ethiopia, but he did not consider the LCI data for electric power consumption. Similarly, Sahle and Potting (2013) carried out LCA for rose production in Ethiopia using LCI data developed for different geographies and electricity production technology mixes from other jurisdictions. The overall objective of this study is, thus, to evaluate and generate an average LCA data for operational wind farms in Ethiopia.

4.2. Existing wind power systems in Ethiopia

4.2.1. Technical Specifications

The wind power system consists of three wind farms, namely Ashegoda wind farm (ASWF), Adama wind farm I (AWF I) and Adama wind farm II (AWF II). ASWF comprises of two different wind turbine models; namely GEV HP and ECO74 type wind turbines. It is located about 20 km from Mekelle city in the Tigray Regional State, about 720 km north of the country's capital, Addis Ababa, and about 695 km from Djibouti seaport. AWF I and AWF II are located about 5 km from Adama city and about 95 km from the capital. **Table 4.1** presents technical parameters of the three wind farms including installed capacities, estimated and realized electricity generation, and capacity factors. The installed capacities describe the maximum power and energy outputs if the wind farms were operated at rated wind speeds. Since wind speeds at the sites cannot be constant throughout the year, annual energy outputs are usually estimated using power curves of wind turbines. Using statistical method, Eshetu (2010) has estimated the annual energy of Ashegoda wind farm as 362 GWh. Similarly, general procedures have been used to estimate the annual installed electricity generation of AWF I and II.

The average actual electricity generations are calculated for three consecutive years (2015-2017). Based on information obtained from the Ethiopian Electric Power (EEP) information desk, the expected and realized capacity factors were calculated as the ratio of estimated or actual annual electricity generation respectively, and the maximum potential annual electricity generation (Boccard 2009; Cetinay et al. 2017). From **Table 4.1**, the average realized capacity factor (CF) of wind farms in Ethiopia during 2015-2017 was 0.243, which is 34 % lower than the average expected CF value. The average realized CF of the onshore wind power system in UK in 2005-2014 was 0.256 (Crabtree et al., 2015). Similarly, the average realized CFs of typical onshore wind farms in Taiwan, Bolivia and China are reported to be 0.28 (Cheng and Yu, 2013), 0.32 (Mamani et al. 2018), and 0.256 (Wanga et al., 2019) respectively. In general, the realized capacity factors are lower than average estimated values and depend on design and site of wind farms (Boccard 2009) and it may vary considerably depending on days, months and years of data collection(Dagnall et al. 2007; Mamani et al. 2018).

Table 4.1 Production capacities and technical parameters of wind farms in Ethiopia

		ASWF	AWF I	AWF II
Rated power (MW)		120	51	153
Installed annual energy (GWh)		1051	447	1340
Estimated annual energy (GWh)		362[a]	157[b]	488[c]
Estimated Capacity factors (ECF)		0.34	0.35	0.36
Actual energy production (GWh)[d]				
	2015	239	187	245
	2016	198	143	418
	2017	105	100	306
Realized capacity factors (RCFs)				
	2015	0.23	0.42	0.18
	2016	0.19	0.32	0.31
	2017	0.10	0.22	0.23
Average RCFs		**0.17**	**0.32**	**0.24**

Sources: [a] (Eshetu, 2010); [b] (EEP, 2017); [c] (Tadesse, 2014); [d] EEP information desk

Similarly, **Table 4.2** below summarizes the technical specifications of wind turbines constituting wind farms in Ethiopia based on local literature. The annual average wind speeds and power densities of the three farms are above 8 m/s and 400 W/m^2 respectively.

Table 4.2 Summary of relevant technical data of wind turbines in Ethiopian wind energy systems

Parameters	ASWF[a]		AWF I [b]	AWF II[c]
Type of wind turbine	GV HP	ECO 74	GW77/1500	SE7715
Axis of rotation	Horizontal	Horizontal	Horizontal	Horizontal
Number of wind turbines	30	54	34	102
Number of blades	2	3	3	3
Rotor diameter, m	62	74	77	77
Hub height, m	70	80	65	70
Rated power, kW	100	1670	1500	1500
Rated voltage, volts	690	690	690	690
Cut-in & cut-out wind speeds, m/s	3, 25	3, 25	3, 25	3, 25
Rated wind speed, m/s	15.5	15.5	11	11
Power density, in W/m^2	571	571	654[d]	440
Annual average wind speed, m/s	8.5	8.5	8.11	8.22
Wind class as per IEC 61400-1	Class IIA	Class IIA	Class IIA	Class IIA
Type of wind turbine generators	DFIG	DFIG	PMDD	DFIG

NB: DFIG = doubly-fed induction generator; PMDD= permanent magnet direct drive
Source: [a] (Wudu, 2015), [b] (EEP, 2017), [c] (Tadesse, 2014), [d] (Hydrochina Corporation, 2009)

4.2.2. Internal and grid connection

Large scale wind farms can be organized into four subsystems. **Figure 4.1** shows the configuration of the main components of each wind farm including wind turbines (denoted by 'G') and medium voltage (MV) and high voltage (HV) transformers connected with cables and overhead transmission lines. For simplicity, MV and HV switchgear devices are not included in the figure. AWF I and AWF II are connected to the grid through high voltage overhead transmission lines, whereas ASWF is directly linked to the Alamata-Mekelle segment of the national grid. In Ashegoda wind farm, the thirty 1 MW GEV HP turbines are interconnected to one another through underground cables and grouped into two clusters using two CGM.3 gas insulated switchgears with metallic enclosure.

Similarly, the fifty-four 1.67 MW Alstom ECO 74 turbines are interconnected to one another through underground cables and then grouped and linked with four CGM.3 gas insulated MV collection cubicles or switchgears with metallic enclosure. Each cluster is connected to a busbar in the MV and low voltage (LV) distribution room in the central substation through 33 kV overhead lines and metal poles. The MV busbar is connected to two 63 MVA transformers and air insulated switchgear supplied by GE Grid Solutions and its subsidiaries in France and India. Finally, the 230/33 kV high voltage (HV) substation is connected to 230 kV national grid, with no additional HV transmission line.

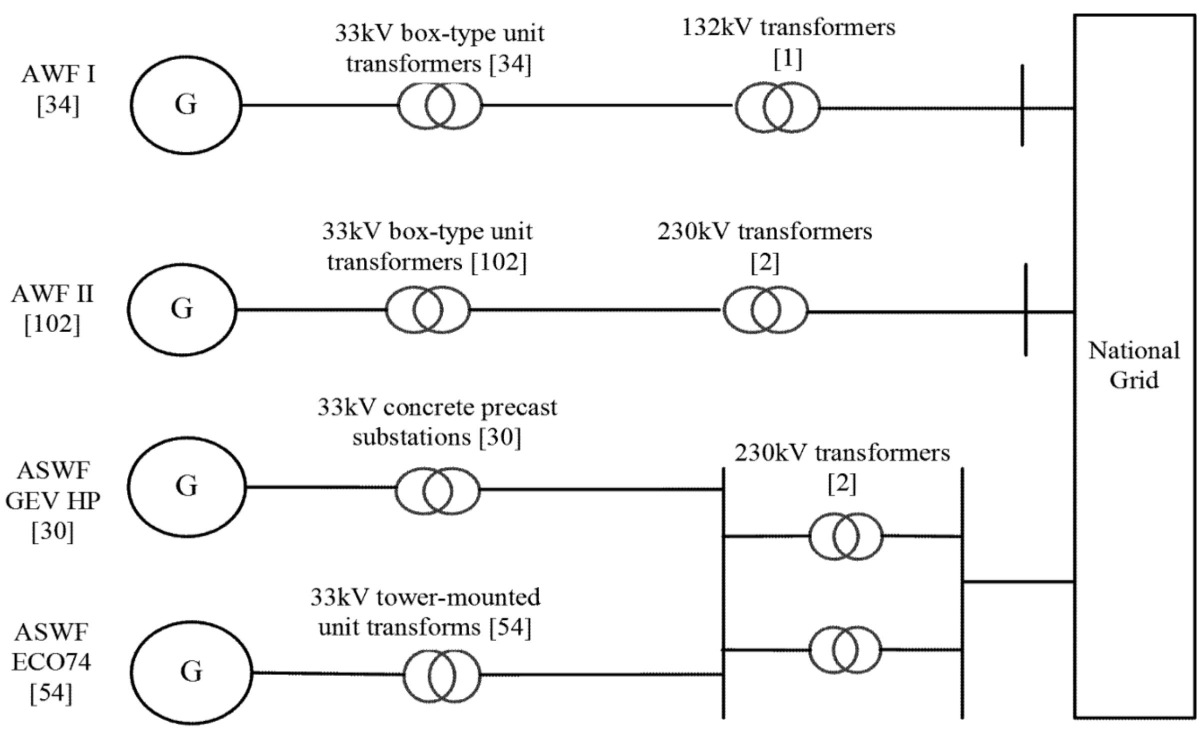


Figure 4.1 Configuration of wind farms in Ethiopia

N.B. Numbers in brackets indicate quantity of each item

AWF-I comprises of thirty-four 1.5 MW Goldwind GW 77/1500 wind turbines. Each wind turbine generator is connected to 33 step-up transformers through 0.6/1 kV cables, and two 33 kV overhead lines with angle iron towers are connected to 33 kV busbar of a 132 kV substation with a power transformer of 55 MVA. Finally, the HV terminal is connected to the grid using 8 km long 132 kV single circuit overhead line with steel truss towers. Similarly, AWF II consists of 102 Sany SE7715 type wind turbines of 1.5 MW each, where electricity generated in each wind generator passes through 0.6/1 kV cables to 33 kV box-type transformer and connected to the 230 kV substation through a 78 km long 33 kV overhead transmission line using 403 angle iron towers. The 230 kV substation is equipped with two 230 kV step-up transformers and high voltage air insulated switchgear. Ultimately, the 230 kV substation is connected to Koka substation by a 13 km long 230 kV transmission line mounted on 43 angle iron towers.

4.3. Methodology

This section discusses the materials and methods used in this study. The rest of the article is mainly structured in line with the ISO standardized LCA framework (ISO, 2006a) that involves four main steps: goal and scope definition, inventory analysis, impact assessment and interpretation.

4.3.1. Goal and scope definition

The intended aim of this study is to contribute to the creation of an average LCA dataset for background systems in Ethiopia such as the national electricity grid. It attempts to estimate and evaluate the environmental impacts of currently operational wind farms from raw material acquisition, component manufacturing, operation and end of life for the reference period of 2015-2017. It also examines the relative contribution of subsystems such as wind turbines and distribution and transmission connections to the total impact. The target audiences include academicians, LCA practitioners, developers, utility companies, and policy makers.

4.3.1.1. Functional unit

The generation of 1 kWh of average electricity from all three wind farms connected to the national grid system is considered as the functional unit for this LCA study. All inputs and outputs of the study system are, therefore, expressed in relation to this functional unit.

4.3.1.2. System boundaries and omissions

Defining system boundaries includes identifying life cycle stages and processes within the total wind power system; and specifying the spatial, temporal and technology aspects of the processes.

Life cycle stages: As shown in **Figure 4.2**, the present LCA study considers all life cycle stages of the wind power system from cradle-to-grave covering: raw materials extraction and processing, component manufacturing, construction and installation, operation and maintenance, and dismantling and end of life waste management.

Raw material production stage: the manufacturing of materials like steel, aluminum, and copper receive scraps in addition to primary natural resources from the environment. It is assumed that the amounts of secondary metal scraps used in these processes are derived from metal scraps reprocessing at the end-of-life stage handled based on the recycled content (cut-off) approach. In this method, the amount of metal scraps recycled would be equal to the amount of secondary metal scarp used in the steel production (e.g., Frischknecht 2010, PE Americas 2010, Nakatani 2014).

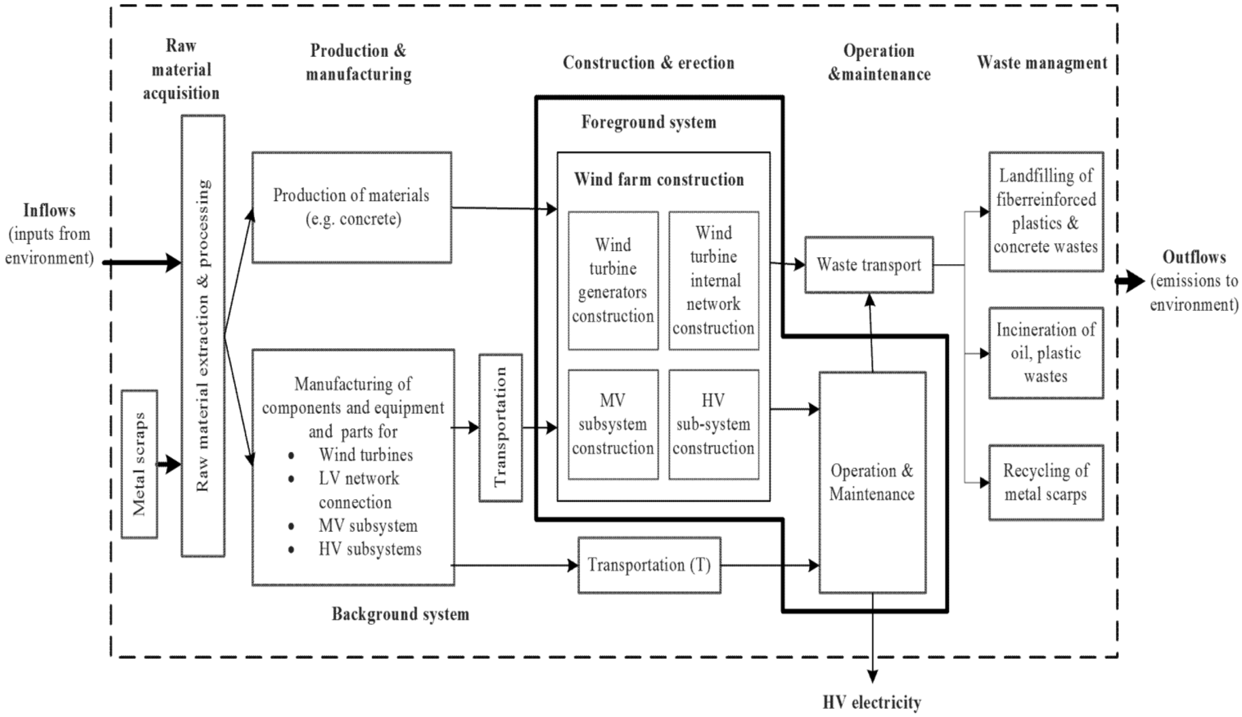


Figure 4.2 System boundaries for the life cycle assessment (LCA) study

Manufacturing stage: Most materials (reinforcing steels, oils, fuels) and all electromechanical components of the wind farms were manufactured mainly in Europe and China and transported to Ethiopia through Djibouti port. All sea and portion of road transportations took place outside Ethiopia. On the other hand, most construction materials such as cement, gravel, and water were supplied from domestic factories and facilities. Energy consumption for the manufacturing of components such as cables and switchgear devices like circuit breakers, current and voltage measurement instruments, disconnector and switches were not included as it is deemed of negligible contribution.

Transportation: Road transport by trucks was considered for moving components and equipment from manufacturing facilities to the nearest seaport of countries of suppliers; Djibouti seaport to wind farm sites; and for transporting wastes from these sites to treatment facilities. Sea transport was considered between seaports. Whenever the maximum weights of transported goods are known, the appropriate lorry types were selected; otherwise, the unspecified option in Ecoinvent database version 3.01 was applied. In all cases, EURO3 engine category was used from the transport dataset. Transportation of workers and construction machineries, as well as fuel consumption by cranes during installation are not modeled. Sea and road transport distances from suppliers to wind farms sites are presented in **Table 4.3**.

Table 4.3 Supplier and transportation sea and road distances, from suppliers to wind farms

Wind farms	Components	Suppliers	Sea transport (km)	Truck transport (km)
ASWF				
	Blades	ACO (Vergnet), Béziers city, France	5475	756
GEV HP	Nacelle assembly	Vergnet, Ormes city, France	7927	1054
	Towers	Vergnet, Ormes city, France	7927	1054
	Concrete prefabricated transformer substation	Uniblok, Velatia, Spain	5638	1065
ECO74	Blades	LM blade, Bunuel city, Spain	7688	954
	Nacelle assembly	ALSTOM, Bunuel city, Spain	6130	961
	Towers	ALSTOM, Coreses city, Spain	7110	1078
GEV HP and ECO74	MV collection cubicles	Ormazabal, Velatia, Spain	7688	721
	Transformer (230kV)	Shanghai Baoshan Transformers Co., Ltd.	11062	695
	Circuit breaker and LA	AREVRA T&D Villeurbanne, France	5460	1033
	Others HV switchgear devices	AREVRA T&D India Limited, India	5491	1016
AWF I	Blades	LM blade, Tianjin, China	11776	887
	Nacelle assembly	Goldwind, Xinjiang, China	12038	3454
	Towers	Goldwind, Xinjiang, China	12038	3454
	Transformer (132kV)	Baoding Tianwei Group Tebian Electric Co.	11514	1039
	HV switchgear	Xi'an XD High Voltage Apparatus Co., Ltd.	11062	2229
AWF II	Blades	LM blade (China)	11776	887
	Nacelle assembly	Sany, Beijing, China	12038	963
	Towers	Sany, Beijing, China	12038	963
	Transformers (230kV)	Baoding Tianwei Group Tebian Electric	11062	1039
	HV switchgear	Different, jiangsu, china	11062	1100

Construction stage: The erection of wind turbines, internal network system, MV system and HV system were modeled separately with the aim to estimate their contribution to the total environmental impacts and the construction of the wind farm. The constructions of buildings and facilities in the substations are considered under the HV system. The construction of measuring and control electronics devices in the control rooms and onsite waste treatment activities in the wind farms are not considered.

Operation and maintenance stage: Maintenance activities cover repair and replacement of parts, oil and lubricant changes, and transportation of these materials and technicians to wind farms. Replacement of lubricating oils is assumed once per three years based on personal communication with experts in wind farm sites. On other hand, there is no agreement on the frequency of material replacement of components and parts in the wind power systems. For systems of 20 years lifetime, Haapala and Prempreeda (2014) considered a 100% replacement rates for blade, gearbox and generator, whereas Xu et al. (2018) assumed replacement rates of 50% for blades and gearboxes and 15% replacement for PMDD wind turbine generators. On the other hand, Zimmermann et al. (2013) suggest an exchange rates of 50%, 50% and 30% for blades, gearboxes and generators respectively in double fed induction generator (DFIG) type wind turbines. To account for these variations, rate of replacement of components and parts and its effect on the result is further discussed under assumption and sensitivity analysis sections.

End of life stage: At end of the service period, wind farms are considered to be dismantled with discarded materials covering concrete from foundations, fiber-reinforced plastics mainly from the rotor blades, metals scarp of components and parts, used oils and lubricants transported to waste disposal facilities. As most of the first installations of wind farms in different parts of the world are still operational, there is scarce practical information related to their end-of-life stage (Ozoemena et al. 2018; Wanga et al. 2019). Recycling, landfilling and incineration are widely used in the literature for the modelling of end of life of different parts of wind power systems. Previous studies (Martínez et al. 2009a; Haapala and Prempreeda 2014; Xu et al. 2018) modeled fiber-reinforced plastic composites and concrete with 100% landfilling, lubricants and plastics for 100% incineration, and scrap metals for recycling, landfilling or incineration processes. There are two major and commonly applied approaches of accounting for benefits and burdens of recycling: recycled content method and end-of-life recycling (EOLR) method. The recycled content (cut-off) method requires recycling of an amount of secondary materials equal to the recycled content used in the production of metals in the analyzed system (Frischknecht 2010; PE Americas 2010; Shen et al. 2010). According to Ecoinvent database 3.01; recycled contents of 37%, 35%, and 39% are considered for steel, copper and aluminum respectively. In the EOLR approach, the analyzed system is credited for the amount of secondary materials produced above the recycled content in the production phase for the possible reduction of environmental impacts resulting from the reduced demand for primary material from nature (Nakatani 2014; Frischknecht 2010). The environmental burdens from recycling were not taken into consideration in this study given the insufficient information related to material recycling in Ethiopia. In addition, due to lack of information about final disposal processes such as landfilling and incineration of wastes in the country, these processes were modeled using Ecoinvent waste treatment processes. The distance between the wind farms and treatment facilities were assumed as 25 and 100 km for Ashegoda and Adama wind farms respectively taking the proximity to the cities of Mekelle and Addis Ababa respectively.

Spatial boundaries: As explained in the manufacturing stage, while many materials and components of the analyzed wind farms were imported, still relatively large number of inputs (e.g., cement, aggregates and water) and civil works were sourced within Ethiopia. The system boundary of this study can, thus, be considered global from inputs perspective. However, the foreground system covering the construction, and operation and maintenance processes are in Ethiopia, further justifying the need for this study.

Temporal boundaries: A lifespan of 20 years extending from erection to demolition was considered for each wind farm. The baseline time period for data collection was between 2015 and 2017. A three-year average realized electricity generation and consumption data was used to calculate total lifetime electricity generation and consumption of mineral oils. The analysis considered a 100-year time horizon for global warming potentials (GWP).

Technology coverage: As wind power systems are new to Ethiopia, it is assumed that new and current technologies represent the analyzed wind power system.

4.3.1.3. Allocation

For allocation in upstream and downstream processes (e.g., fuel production and waste treatment), the Ecoinvent database version 3.01 with a system model 'allocation, default, recycled content' was applied.

4.3.2. Inventory data collection

For this study, the process-based attributional LCA system model was applied. More information can be found about attributional LCI modeling in Ekvall and Weidema (2004), Curran et al. (2005), and Heijungs et al. (2009), and about process-based LCI in

Hendrickson et al. (1997) and Majeau-Bettez et al. (2011). The 'Ecoinvent 3 - allocation, default unit' library integrated into SimaPro version 8.0.3.14 was used for system modelling and LCI data source. Technical as-built drawings and documents provided by suppliers and contractors were main sources of material and energy consumption. Input data on consumption of mineral oils and output data on daily and annual power generation were obtained from offices at wind farm sites and central information desk of Ethiopian Electric Power (EEP). The distances between seaports are computed using an online calculator at sea-distances.org. When primary data were unavailable, secondary data from literature and databases were used. Life cycle inventories for material production, background electricity and waste treatment activities were taken from the Ecoinvent 3.01database. **Table 4.4** presents detailed information about types and sources of data.

Table 4.4 LCI data types and their sources

Life cycle stage	**Data collcted**	**Data source**
Raw materials extraction and production	LCI dataset for raw material used in component manufacturing	Ecoinvent database version 3.01 in SimaPro
	Data on clinker and cement production	Local cement industries
	Gravel and sand production	Ecoinvent database version 3.01
	Amount and transported distance for cement and aggregates	Personal communication with operators in wind farms
Component manufacturing	Material types and weights of AWF I	As-built drawings, feasibility and commissioning reports, and (Xu et al., 2018) (Polinder et al., 2005) (Bang et al. 2008) (Yang et al., 2012)
	Material types and weights of AWF II	As-built drawings and feasibility report
	Material types and weights of ASWF I and ASWF II	Technical drawings and documents from suppliers, and (D'Souza et al., 2011), (Carrascal and Pablo, 2014), (Chipindula et al., 2018), (Guezuraga et al., 2012b)
	Types and weights of materials for transformers	Supplier technical drawings and (ABB, 2003)

Life cycle stage	Data collcted	Data source
	Quantities and composition substation switchgear devices like CB, CT, VT, DS and LA	Technical drawings and specifications from suppliers and (Wang et al., 2011)
	Material composition & weight of cables	Supplier technical documents
Operation and maintenance	Daily electricity production	EEP information desk
	Estimated annual electricity production	Feasibility study reports, commissioning report and (Eshetu, 2010)
	Information on types and capacities of wind turbines	Contract documents, reports, as-built drawings personal observation at power plants and
Construction and erection	Oil consumption in wind turbines	Bincards in wind farm sites
	Amount of concrete and reinforcing steel used.	Contractors reports & contract document
	Concrete mixdesign	(Dinku et al., 2002)
	Types and quantities of towers and cables	Technical drawings, contract document and constructors' reports
	Transport distances	Suppliers profiles and online sea-distance calculator at SEA DISTANCE.ORG
End of life stage	LCI datasets for metal scraps, waste plastics and glasses, etc.	Ecoinvent 3.01database in SimaPro software version 8.0.3.14.

The demand in material and energy needed for construction and operation of wind power plants is related to the annual electricity generated. **Table 4.5** summarizes the life cycle inventory data used in the analysis for the generation of 1 kWh of electricity. For instance, the total consumption for all classes of concrete to construct the whole wind power system is about $6.56*10^{-6}$ m^3/kWh electricity generated. This results in a consumption of about $1.44*10^{-3}$ kg cement, $2.61*10^{-3}$ kg sand, $5.01*10^{-3}$ kg gravel, and $6.24*10^{-4}$ kg water per 1 kWh electricity generated (Dinku et al., 2002). Iron and steel are other important material inputs. The consumption of reinforcing steel, low-alloyed steel, cast iron, and chromium steel per 1 kWh electricity generated are $3.62*10^{-2}$, $3.13*10^{-3}$, $5.25*10^{-4}$, and $1.27*10^{-4}$ kg, respectively. The detail life cycle inventory data used in the analysis for the generation of 1 kWh of electricity is listed in **Annex B**. It groups the input inventory according to subsystems (wind turbines, internal connection network, medium voltage and high voltage) and materials for replacing of components as they are modelled.

Table 4.5 The life cycle inventory data of wind power sytem for the generation of 1 kWh of electricity

Materials	Unit	Pre-operation	Operation and maintenance	Total
Adhesives	kg	1.59E-05	7.91E-06	2.38E-05
Aluminum	kg	8.01E-05	4.46E-07	8.06E-05
Blasa wood	kg	3.40E-06	1.70E-06	5.09E-06
Brass	kg	5.29E-07	7.01E-09	5.36E-07
Cables	kg	4.79E-06	2.79E-07	5.07E-06
Cast iron	kg	4.77E-04	4.88E-05	5.25E-04
Chromium steel	kg	1.09E-04	1.86E-05	1.27E-04
Copper	kg	5.32E-05		5.32E-05
Electrical/electronic component	kg	9.23E-06	3.07E-06	1.23E-05
Electronics, for control units	kg	4.95E-10	7.25E-07	7.25E-07
Epoxy resin	kg	7.65E-05		7.65E-05
GFR (Glass fiber reinforced plastic)	kg	2.23E-05		2.23E-05
Glass fiber	kg	1.64E-04		1.64E-04
Kraft paper	kg	1.79E-06		1.79E-06
Low alloyed steel	kg	3.13E-03	2.25E-07	3.13E-03
Lubricant /hydraulic oil	kg	5.96E-06	8.15E-05	8.75E-05
Paint	kg	5.51E-06		5.51E-06
Permanent magnet	kg	8.10E-06		8.10E-06
Polyester resin	kg	5.85E-07		5.85E-07
Polymers	kg	1.20E-05		1.20E-05
Porcelain	kg	1.07E-05		1.07E-05
PVC	kg	2.04E-07	2.34E-06	2.55E-06
Reinforcing steel	kg	3.62E-02	5.36E-07	3.62E-02
Sand	kg	5.19E-06	3.80E-05	4.31E-05
Sulfur hexafluoride	kg	3.55E-08	3.97E-06	4.00E-06
XLPE	kg	4.62E-06		4.62E-06
Zinc	kg	1.10E-07		1.10E-07
Zinc oxide	kg	2.36E-08		2.36E-08
Mineral oil (20 years consumption)	kg			0.00E+00
Land requirement	m2	3.67E-04		3.67E-04
Concrete	m3	6.56E-06		6.56E-06
Excavation, hydraulic digger	m3	1.17E-03		1.17E-03
Heat, natural gas	MJ	1.50E-04		1.50E-04
Electricity, medium voltage	kWh	1.08E-02		1.08E-02
Road transport	tkm	0.006069	0.001763	0.007833
Sea transport	tkm	4.77E-02	6.57E-05	4.78E-02

4.3.3 Impact assessment methods

There are a number of different methods to carry out life cycle impact assessment (LCIA) (EC-JRC 2010; Hischier et al. 2010; Menoufi 2011; Bueno et al. 2016). CML, IMPACT 2002+, and ReCiPe 2008 are the most commonly used LCIA methods (Ekvall and Weidema, 2004) that are integrated into SimaPro 8.0.3.14 software. ReCiPe 2008 covering a wide range of environmental impacts with 18 midpoint category indicators is selected for this study, see **Table 4.6**. Moreover, the CML method is used for comparing the results of impact categories with literature values as corresponding ReCiPe values for these impact categories were not found in the literature.

For energy, an indicator widely used in LCA studies, namely, the cumulative energy demand (CED) method is applied covering both nonrenewable and renewable resources (Sad, 2015). The energy return on (energy) investment (EROI) is also calculated as an additional energy performance indicator (Murphy et al. 2016; Kittner et al. 2016; Raugei and Leccisi 2016; Hischier et al. 2018; Walmsley et al. 2018).

4.3.4. Key assumptions and Limitations

The main assumptions and limitations include:

- The wind farms lifetime is assumed 20 years in line with many LCA studies while shorter and longer lifetimes are considered in the sensitivity analysis.
- Based on previous studies (Zimmermann et al. 2013; Haapala and Prempreeda 2014; Xu et al. 2018), component replacement rates of 50% for blades and gearboxes, and 30% for generators were used in the DFIG type wind turbines used in ASWF and AWF II. Similarly, replacement rates of 50% for blades and 15% for generators have been used in the PMDD type wind turbine models used in AWF I.

- Electricity mix of main suppliers is used to represent manufacturing of wind farm components and parts. Accordingly, Chinese medium electricity dataset was used for AWF I and II, and the France and Spain cases were used for GEV HP 1 MW and ECO 74 1.67 MW wind turbines of ASWF respectively.
- Norwegian electricity mix dataset is used as a proxy to model the electricity used in local cement and concrete production and concrete placing as both Ethiopian grid and Norwegian grid are dominated by hydropower and there is no local dataset available.

4.4. Results and discussion

Table 4.6 presents the total average potential environmental impacts of three operating onshore wind farms using the method ReCiPe 2008 midpoint V1.10/World ReCiPe H. The impact category indicators were calculated per 1 kWh of electricity generated and delivered to the grid as weighted average of the wind farms.

4.4.1. Potential environmental impacts – total system

In this section, the top ten impact category indicators selected based on normalized values at midpoint level are briefly discussed. These include climate change (CC), fossil depletion (FD), freshwater ecotoxicity (FWET), freshwater eutrophication (FWEU), human toxicity (HT), metal depletion (MD), marine ecotoxicity (MET), particulate matter formation (PMF), photochemical oxidant formation (POF) and terrestrial acidification (TA). **Figure 4.3** below shows the contribution analysis of pre-operation phase, operation and maintenance, and waste disposal phases to the ten impact category indicators. The pre-operation phase consisting of raw materials acquisition, manufacturing and installation of wind farms is the largest contributor, with its share ranging between 86% for FD and 96%

for MD. In general, the analysis shows that transportation (mainly transporting of components and equipment to sites) accounts for less than 1% for FWTU, HT, and MD, while for the rest of impact categories, its contribution ranges between 1.6% and 22%.

Table 4.6 Average LCIA results of wind farms at national grid per functional unit (1kWh)

Impact category	Unit	ASWF	AWF I	AWF II	Mean	St.DEV
Climate change	g CO_2 eq.	36.41	28.57	35.97	33.649	4.404
Ozone depletion	g CFC-11 eq.	2.1E-06	1.2E-06	1.0E-06	1.4E-06	6.1E-07
Terrestrial acidification	g SO_2 eq.	0.197	0.217	0.229	0.215	0.016
Freshwater eutrophication	g P eq.	0.005	0.006	0.003	0.005	0.001
Marine eutrophication	g N eq.	0.009	0.006	0.008	0.007	0.001
Human toxicity	g 1,4-DCB eq.	10.39	12.11	7.23	9.909	2.474
Photochemical oxidant formation	g NMVOC eq.	0.154	0.124	0.154	0.144	0.017
Particulate matter formation	g PM10 eq.	0.103	0.086	0.100	0.096	0.009
Terrestrial ecotoxicity	g 1,4-DCB eq.	0.004	0.004	0.002	0.003	0.001
Freshwater ecotoxicity	g 1,4-DCB eq.	0.024	0.031	0.016	0.023	0.007
Marine ecotoxicity	g 1,4-DCB eq.	0.103	0.127	0.065	0.098	0.031
Ionizing radiation	Bq U^{235} eq.	1.745	0.496	0.612	0.951	6.9E-01
Agricultural land occupation	m^2a	8.9E-04	5.7E-04	6.9E-04	7.1E-04	1.6E-04
Urban land occupation	m^2a	1.1E-03	7.0E-04	8.6E-04	8.9E-04	2.0E-04
Natural land transformation	m^2	2.3E-06	1.7E-06	2.8E-07	1.4E-06	1.0E-06
Water depletion	m^3	1.8E-01	9.5E-02	1.1E-01	1.3E-01	4.7E-02
Metal depletion	g Fe eq.	26.025	14.844	15.317	18.729	6.324
Fossil depletion	g oil eq.	9.206	6.529	8.101	7.945	1.345

4.4.1.1. Climate change (CC)

The average total greenhouse gases (GHG) emission intensity of the analyzed wind power system was 33.6 g CO_2 eq./kWh. The corresponding values from the literature are in the 28.1 to 46 g CO_2 eq./kWh range (Asdrubali et al. 2015; Navarro-Pineda et al. 2017; Wanga et al. 2019). The major contributing flows to this impact category indicator are carbon dioxide (90%) followed by methane (9%) from fossil sources associated with the production and use of materials and energy at different parts of the life cycle. The pre-operation, operation and maintenance, and waste disposal phase constitute about 88%, 9% and 3% of the total impact respectively. In terms of pre-operation, the manufacturing of wind turbines, internal connection network, HV subsystem and MV subsystem, constitute 67%, 12%, 5.3%, and 3.2% respectively. Further breakdown of the manufacturing stage into its components shows that nacelles (30%), towers (17%), and rotors (11%) as the largest contributors and responsible for more than 58% of the total GHG emissions from the system. Transformers represent 12.4% (i.e., unit transformers with 8.7% and power transformers with 3.8%) while other parts cover the remaining 3.1%. The pre-operation phase contributes the largest share of the GHG emission mainly given the construction of wind energy consumes large amount of materials and energy.

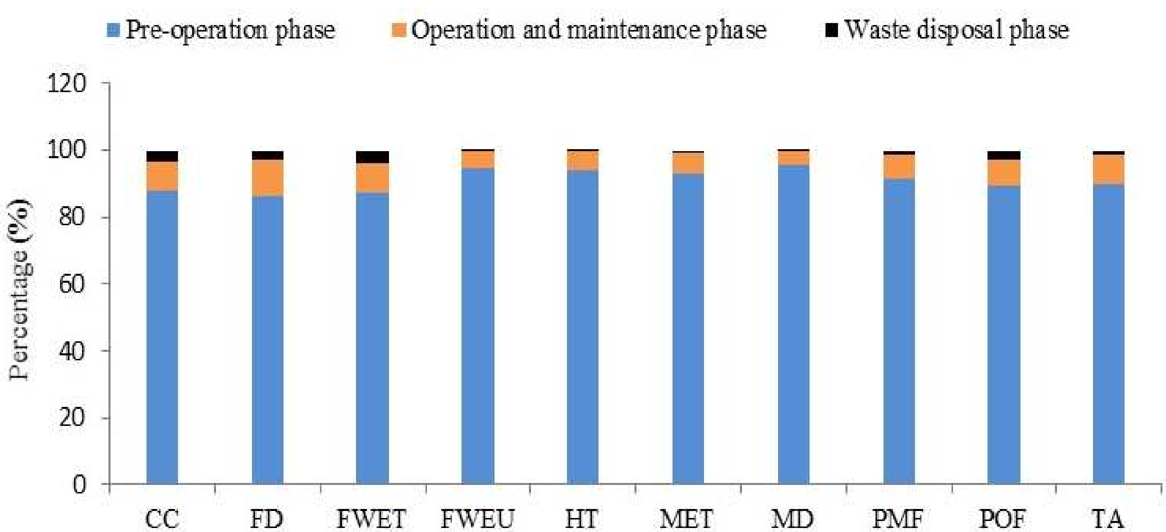


Figure 4.3 Percentage contribution of life cycle stages to selected environmental impacts

4.4.1.2. Human toxicity (HT)

Human toxicity is used as an indicator of impacts on human health due to substances released to soil, water, and air. In this study, human toxicity in 1, 4-dicholorobenzene (DCB) equivalent is about 9.9 g per kWh, which is closer to the lower end of the literature range of 4 to 54.6 g 1,4-DCB eq./kWh (Abeliotis and Pactiti 2014; Xu et al. 2018; Ozoemena et al. 2018; Wanga et al. 2019). The calculated impact is related to the emission of toxic metals into air mainly during the production of copper, cast iron, and steel (together contributing about 85%) used in the manufacturing and operation of wind farms. The pre-operation phase accounts for 94% of the total impact, because this phase requires higher amount of these metals. In terms of pollutant flows, arsenic, mercury, lead, and cadmium emitted into air comprise more than 90% of the total impacts while the release of arsenic, barium, and manganese into water systems contribute about 4% of the impact.

4.4.1.3. Metal depletion (MD)

This impact category indicator quantifies the depletion of naturally occurring mineral resources. For this study, the ReCiPe 2008 method gives an average metal depletion potential of 18.7 g Fe eq./kWh. As there were no corresponding values in the literature based on the same method using the same impact category indicator, we have instead run the CML IA baseline method for metal depletion to compare our results against other studies. This method gives an average metal depletion potential value of 0.432 mg Sb-eq./kWh for our study, which is higher than the result from Xu et al. (2018) at 0.249 mg Sb-eq./kWh. This variation could potentially be because of the difference in wind turbine models. Xu and coauthors assessed the life cycle environmental impacts of a wind farm composed of gearless or permanent magnet direct drive generators (PMDDGs) type wind turbines with 0.75 and 1.5 MW capacities, whereas this study examined three wind farms consisting of geared and gearless generators capacity ranging from 1 to1.67 MW. Around 95% of the contribution to metal resources depletion in our study comes from the extraction of five ores: iron (22%), manganese (21%), copper (20 %), ferronickel (18%), and chromium (14%). The contribution of the construction and operation and maintenance phases are about 96 and 4% respectively.

4.4.1.4. Fossil depletion (FD)

Fossil depletion used in ReCiPe 2008 method refers to primary nonrenewable energy sources. All forms of renewable energy (Goedkoop et al., 2008) and nuclear energy use (Sad, 2015) are outside this impact category indicator. In this study, the average fossil energy used to generate 1 kWh electricity is about 0.008 kg oil equivalent (i.e., 0.336 MJ/kWh considering energy content of reference fuel as 42 MJ/kg crude oil feedstock) (Goedkoop et al., 2008). The result is higher than the value obtained in Xu et al. (2018) at 0.0934 MJ/kWh, which can be explained by the same reason given in section 4.1.3 above and due to considerable fuel consumption to move components and products from Europe and China to Ethiopia. In terms of contributions, 80% of the fossil depletion impact in this study is due to hard coal production (38%), nylon 6-6 gas-filled production (12%), petroleum and gas production (12%), electricity use (10%), natural gas production (3%), transportation (3%) and waste concrete treatment (2%). The Chinese hard coal mining and electric grid constitute 21% and 9% of the impact category indicator respectively, whereas hard coal mining from South Africa used in cement industry in Ethiopia accounts for only 3% fossil fuel depletion impact.

4.4.1.5. Freshwater eutrophication (FWEU)

Process contribution analysis shows that the phosphate discharged into water systems is the single dominant cause of FWEU accounting for about 99% of the total impact. The contribution of phosphorus release into water and soil is less than one percent. The sources of the pollutants are mineral and coal mining. The pre-operation phase was the major contributor (95%) to the phosphate and phosphorus discharges associated with high demand for material and energy sources. On the other hand, credits from recycling of copper scraps reduce the overall impact by 2%. In this study, the average total freshwater eutrophication (FWEU) is 0.0005 g P eq. /kWh when calculated using the ReCiPe 2008 method. The value is 0.03 g PO_4^{3-}eq./kWh when the CML method is used, which is within the literature range of 0.0227 to 0.103 g PO_4^{3-}eq./kWh (Abeliotis and Pactiti 2014; Navarro-Pineda et al. 2017; Xu et al. 2018; Ozoemena et al. 2018; Wanga et al. 2019).

4.4.1.6. Terrestrial acidification (TA)

The average total terrestrial acidification potential of this study at 0.21 g SO_2 eq./kWh is within the values calculated by Abeliotis and Pactiti (2014), Navarro-Pineda et al. (2017) and Wanga et al. (2019), which ranges between 0.17 and 0.78 g SO_2 eq./kWh. The main contributor to TA is the pre-operation phase of wind farms (90%) followed by the operation and maintenance phase (9%). The processes of power generation, fuel combustion (both in building machines and transportation vehicles), copper production, nylon 6-6 glass-filled production, hard coal production, steel production, and cement production contribute about 51.7%, 15%, 9%, 4.7%, 4.6%, 2.7% and 2.2% of the total impact respectively. The road and sea transportation of components and equipment to sites contributes about 13% of the terrestrial acidification. The major contributing substances are sulfur dioxide (72%) and nitrogen oxides (26%). The contribution of ammonia and other sulfur oxides is negligible.

4.1.7. Photochemical ozone formation (POF)

Nitrogen oxides (NOx) are the most significant pollutants in this impact category, followed by non-methane volatile organic compounds (NMVOC), sulfur dioxide (SO_2), and carbon monoxide from fossil fuels. Each of them contributes about 69%, 16%, 9% and 5% to the total POF respectively. The contribution of benzene, ethane, and methane to the impact is negligible. In terms of sources, electricity generation and supply, transportation of components and equipment to sites, and cement production account for 31%, 20% and 11% to the emissions of POF pollutants respectively. The total photochemical ozone formation indicator value is 0.144 g NMVOC eq./kWh based on the ReCiPe 2008 method. For comparing with literature values, the impact category indicator value calculated using the CML method as 0.013 g C_2H_4 eq./kWh is within the range of 0.009 to 0.17 g C_2H_4 eq./kWh obtained by Abeliotis and Pactiti (2014), Navarro-Pineda et al. (2017), and Wanga et al. (2019).

4.4.1.8. Other impact categories

As shown in **Figure 4.3**, the pattern where pre-operation phase takes a predominant share of the impact as observed in the categories presented above continues for the remaining impact categories. The pre-operation phase of wind farms accounts for approximately 86%, 91% and 93% total impacts of freshwater ecotoxicity (FWET), particulate matter formation (PMF), and marine ecotoxicity (MET) respectively. Nitrogen oxides (NOx), particulates, and sulfur dioxide (SO_2) emitted into the air are the most significant pollutants contributing 23%, 45% and 32% to PMF respectively. Top process contributions to PMF come from processes of electricity generation (32%), metal production (21%), transportation (7.3%), glass-filled nylon 6-6 production (4%), coking (4%), and coal mining (2%). The analysis results show that processes such as waste treatment (35%), natural gas production (25%), gold mining (11%), glass filled nylon-6-6 production (6%), and iron ore beneficiations and steel processing (3%) account for about 80% of the FWET.

Regarding pollutants, the release of heavy metals (e.g., bromine, copper, nickel and zinc) constitute more than 95% of FWET. Heavy metals discharged to air are the main causes of MET. The processes behind the impact of FWET are also the major sources of heavy metal pollutants of MET. The results show that the average impact category indicator values for our study are 0.023 g 1,4-DCB eq./kWh FWET, 0.097 g PM10 eq./kWh PMF, and 0.098 g 1,4-DCB eq./kWh MET.

4.4.2. Energy analysis

The cumulative energy demand (CED) is an energy use indicator widely used in LCA studies (Sad, 2015). The CED method is used to quantify the primary energy usage, both non-renewables and renewables, throughout the life cycle of the analyzed system including direct and indirect uses of energy, but excluding wastes used for energy purposes. The CED method integrated in SimaPro 8.0.3.14 software accounts for seven different categories namely, fossil, nuclear, biomass, wind, solar, geothermal, and hydro. The calculated CED value in our study is 0.393 MJ, which is within the range of mean CED values from the literature (0.007 MJ to 0.425 MJ) for onshore wind turbines obtained by Arvesen and Hertwich (2012). Kubiszewski et al. (2010) used the value of CED to calculate energy return on investment (EROI) that presents energy performance as the ratio of energy generated and energy required to generate that energy using equation 1 (Centre for Sustainable Energy 2017):

$$\mathrm{EROI} = \frac{\text{Energy returned to society}}{\text{Energy requred to get that energy}} \qquad \text{Eq.4.1}$$

Using equation 1 with CED value of 0.393 MJ, the value of EROI would be 9.2. Walmsley and coauthors calculated EROI for New Zealand wind farms over a 20-year lifespan and found that the EROI values range between 6.5 -57.7 with average at 34.3 (Walmsley et al., 2018).

Kubiszewski and coauthors conducted a meta-analysis of net energy return for wind power systems operating in USA and Europe and report an average EROI value of 19.8 (Kubiszewski et al., 2010b).

4.4.4. Comparison between analyzed wind farms

The life cycle environmental impacts for each wind farm calculated per kWh of electricity generated is given in table 6. Ashegoda wind farm (ASWF) and Adama wind farm II (AWF II) have higher GHG emission equivalents than the average of the total wind power system. In addition, the rest of impact category indicator results of ASWF are greater than the average corresponding impact values of the total system except for the terrestrial acidification potential. However, there is no clear trend between the impacts of wind farms as range of factors including capacities or type of wind turbines technology play a role. As shown in table 6, ASWF and AWF II, for example, have significant differences including in natural land transformation, ionizing radiation, freshwater eutrophication, human toxicity, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, and metal depletion while they have comparable impacts in climate change, fossil depletion and marine eutrophication. A detailed investigation into their input shows that ASWF consumed more higher-grade steel (chromium steel) than AWF II. In the SimaPro database, one can see that the production of 1 kg hot rolled chromium steel 18/8 has 2.4 more human toxicity than the production of same amount of hot rolled low-alloyed steel. In contrast, the potential impacts of terrestrial acidification (TA) for AWF II is larger than its counterpart value for ASWF due to that fact that AWF II consumed more fuels during transportation and construction (excavation).

Adam I wind farm (AWF I) is composed of wind turbines with same capacity (1.5 MW) as that of AWF II or smaller size wind turbines than ASWF (1.67 MW). Moreover, wind turbines in AWF I are gearless or direct drive permanent magnet generators (PMDDGs), with potentially less materials in the nacelle part. However, it has large toxicity impact category indicators such as freshwater eutrophication, human toxicity, freshwater ecotoxicity, and marine ecotoxicity. This variation is due to, for example, the fact that AWF I consume 5 kg and 2.2 kg more copper and permanent magnet than ASWF and AWF II. As discussed in sections 4.1.2 and 4.1.8 above, copper production is one of the major sources of toxic heavy metals. Generally, this indicates that many factors affect the impacts of wind farms or wind turbines in addition to their sizes. Some of these factors are discussed below.

4.5. Interpretation

The interpretation part in the form of contribution analysis presented in previous sections rely heavily on baseline data and assumptions. The effect of different aspects and parameters on the overall result is tested through sensitivity analysis and scenario analysis as follows.

4.5.1. Sensitivity analysis

In this study, sensitivity analysis was conducted for three important parameters (wind farm life span, replacement rates and capacity factor) and one input variable, transport.

4.5.1.1. Replacement rates

Based on previous LCA studies (Zimmermann et al. 2013; Haapala and Prempreeda 2014; Xu et al. 2018), the baseline scenario of this study considers typical replacement rates for blades, gearboxes, and generators of wind turbines in the analyzed system. To capture the difference in the literature in terms of the frequency of material replacement of components and parts in the wind turbines and to determine the sensitivity of our model to these variations, sensitivity analysis was carried out. The analysis considers no replacement and double replacement rates for comparison with the baseline scenario. **Figure 4.4** shows that doubling the replacement rates increases all impacts categories in the range of 18% to 25% compared to the baseline scenario; and 34% to 50% compared to no replacement scenario. This is generally in agreement with the results obtained by Vestas (2015) where increasing the replacement rates has an escalating effect in all impact categories.

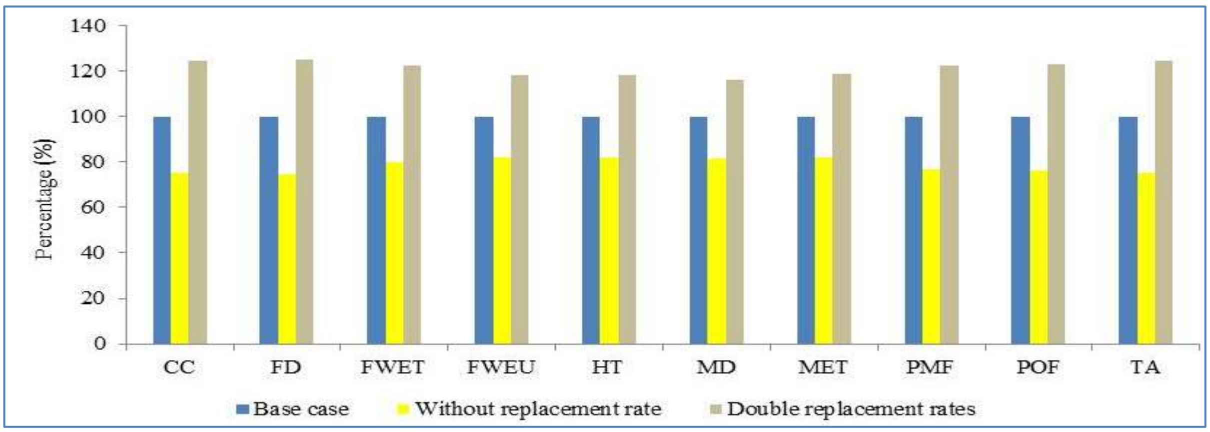


Figure 4.4 Sensitivity analysis results of different replacement rates of wind turbine part compared to base case

4.5.1.2. Wind farm Lifespan

Hughes (2012) has suggested that 12 to 15 years would be more realistic and economical. However, the lifespan of onshore horizontal axis wind turbines is often assumed to be 20 years (Ardente et al. 2008; Yang and Chen 2013; Xu et al. 2018; Ozoemena et al. 2018; Wanga et al. 2019). According to Center for Sustainable Energy (2017) and Soe et al. (2015), depending on site wind conditions and maintenance qualities, turbines could last for 25 years. Iberdrola (2018), for example, took the same lifespan of 25 years. To capture these variations, a sensitivity analysis for 15 and 25 years was conducted to examine the effect of lifespan on the impact category indicator results. As the change in lifespan potentially affects the assumption in the baseline scenario on the typical replacement rates of components, component replacement rates were adjusted accordingly. For the lifespan of 15 years, replacement rates of 37.5%, 37.5% and 22.5% for blades, gearboxes, and generators in DFIG respectively; and 37.5% and 5.6% for blades and generators in PMDD-type wind turbines respectively were considered.

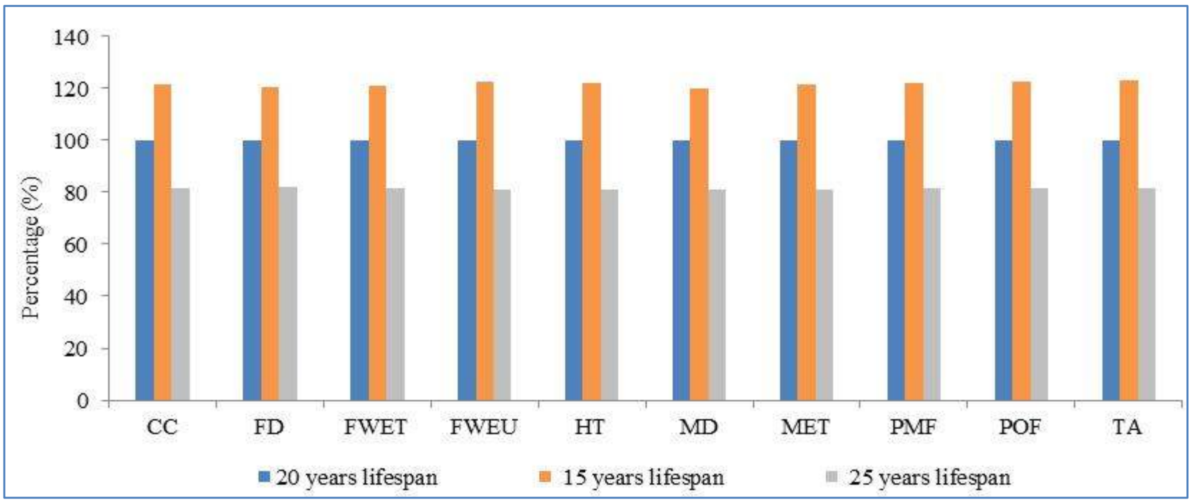


Figure 4.4 Sensitivity analysis results of different assumptions in wind turbine lifespan (20-year lifespan as base case)

Similarly, for the lifespan of 25 years, replacement rates of 62.5%, 62.5% and 37.5% for blades, gearboxes, and generators in DFIG respectively; and 62.5% and 9.4% for blades and generators in PMDD-type wind turbines respectively were used. As shown in **Figure 4.5** above, reducing lifespan of wind farms by 5 years would result in an increase between 20% and 23% in all impact categories while increasing the lifespan by 5 years brings 18% to 22%. reduction of impacts. These values are consistent with previous LCA studies on hypothetical wind farms (D'Souza et al., 2011; Vestas, 2015).

4.5.1.3. Capacity factors

A capacity factor (CF) for the energy generating system is a vital variable used to determine the efficiency of power plants. As data about site-specific conditions is either unavailable or of not reliable quality, estimated energy production and CFs are calculated under uncertainties and reflecting variations. In this sensitivity analysis, two life cycle energy generations were simulated; estimated annual energy generation calculated from the power curves of the respective sites (Eshetu, 2010; Tadesse, 2014), and realized average energy generations in order to see how the choice of CF affects the LCA model output. For CF based on realized generation, four subcases were considered; namely three based on the average annual generation for the years 2015, 2016 and 2017 and one based on three-year average generation to study the effect of annual variations. From table 1, the estimated CFs values for ASWF, AWF I, and AWF II are 0.34, 0.35 and 0.36 respectively. Depending on characteristic power curves and local wind conditions, researchers have used different CF values even for wind farms composed of wind turbines of similar capacity. For instance, Ozoemena et al. (2018), Yang and Chen (2013) and Oebels & Pacca (2013) have used CF values of 0.220, 0.258 and 0.343 respectively for wind farms composed of wind turbines of capacity 1.5 MW each in UK, China and Brazil. Similarly, Wang and Sun (2014) and Al-Behadili and El-Osta (2015) have applied CF values of 0.407 and 0.424 respectively for wind farms composed of wind turbines of capacity 1.65 MW each in China and Libya. AWF I and AWF II with 1.5 MW wind turbines have different estimated CF values compared to wind farms in the literature composed of turbines of same size.

In the same table, the realized capacity factors of ASWF vary between 0.1 and 0.23; for AWF I between 0.22 and 0.42 and for AWF II between 0.18 and 0.24 over the three years under investigation. The average realized capacity factors of these wind farms were 0.17, 0.32 and 0.24 respectively. Thus, the average CF value of ASWF is low compared to those values reported in the literature for Italy by Ardente et al. (2008), and for China by Wanga et al. (2019) and Xu et al. (2018), which are 0.19, 0.235, and 0.3 respectively. Moreover, one can see that the average realized CFs of ASWF, AWF I and AWF II are 33.6%, 8.7% and 33.8% less than the estimated CFs. Boccard (2009) showed that realized capacity factors of wind turbines in Europe and USA are 35% lower than the estimated CF values.

Figure 4.6 depicts the effects of estimated and realized productions on the LCA results of the wind power systems. The results show that a 35% reduction between estimated and actual mean annual electricity generations (see Table 4.1 above) would result in 36% to 37% increase in all impact category indicators. For instance, the CO_2-equivalent increases by 36%, which is not far from the 40 % increase obtained by Boccard (2009). By simply looking at the CFs values, one may assume that all indicators will be reduced when the average energy production in 2016 is used compared to the LCA results calculated using the average energy production of 2015. This is not the case as the analysis shows that some impacts like metal depletion, human toxicity, and marine ecotoxicity increased in 2015 (when CF is 0.17) and decreased in 2016 (when CF is 0.32). Similarly, potential impacts of climate change, terrestrial acidification, photochemical oxidant formation and particulate matter formation are reduced in 2017 (when CF is 0.24) compared to 2015. From this, one can see that the CFs of individual wind farms have significant roles in the average total impact of analyzed system when the wind farms use a mix of different technologies.

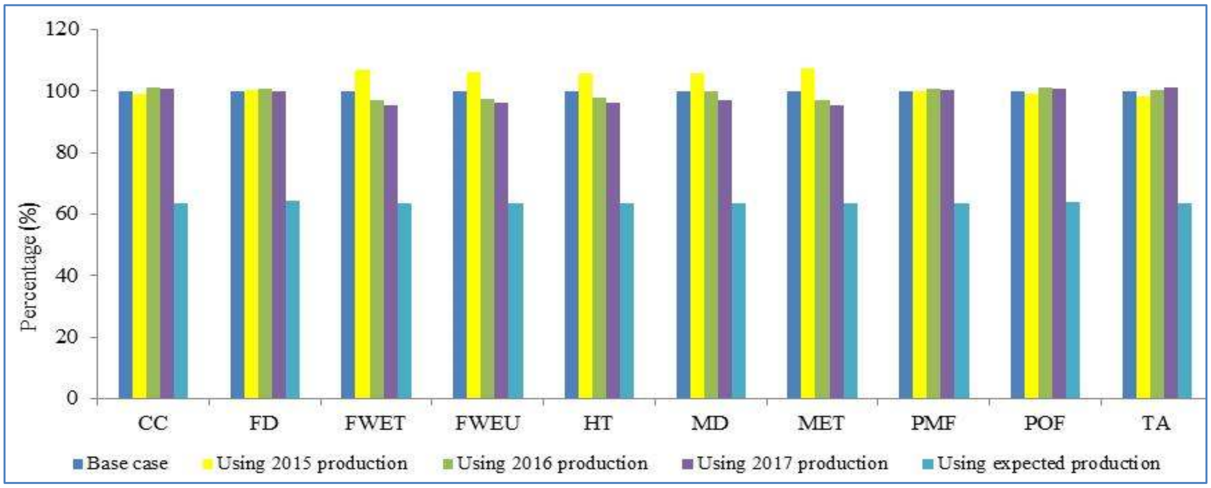


Figure 4.5 Comparison of the effects of estimated and realized production on the LCA results of wind energy system relative to the base case (i.e., using 3-year average production)

4.5.1.4. Material recycling

Waste materials from wind farms can be recycled or disposed of in landfills or incinerated. Haapala and Prempreeda (2014) and Wanga et al. (2019) evaluated the effects of increasing the percentage of material recycling on model results using sensitivity analysis. In our study, as recycling is not considered in the baseline scenario, a sensitivity analysis of metal scarp recycling was carried out in order to understand and incorporate its environmental burdens in the analyzed wind farms. Due to lack of reliable data about the recycling rates of materials in Ethiopia, a recycling rate of 80% was considered for steel, aluminum and copper as best scenario (e.g., Wanga et al. 2019). The analyzed system is credited for amount of secondary materials produced above the recycled contents of steel, copper and aluminum in the production phase for the possible reduction of environmental impacts resulting from the reduced demand for primary materials from nature (Nakatani 2014; Frischknecht 2010). According to SimpaPro software version 8.0.3.14, the recycled contents of steel, copper and, aluminum are about 37%, 34.7% and 39% respectively.

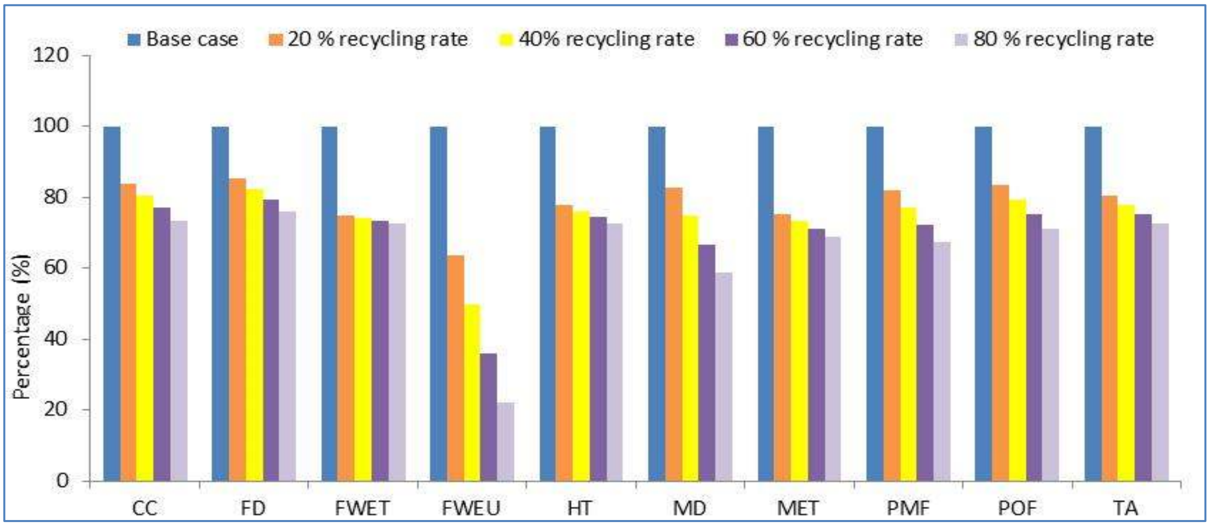


Figure 4.6 Comparison of the effects of recycling rate of metals scraps on the LCA results of wind power system releted to base case (i.e., 0% recycling rate)

Figure 4.7 shows the sensitivity analysis results of recycling rates starting from zero recycling rate (i.e., the baseline scenario) to 80% recycling rate (the best scenario) with 20% intervals. The recycling of steel scraps generally results in reduction in all impact categories. For instance, the GHG emissions at recycling rates of 20% and 80% are about 28 and 25 g CO_2 eq./kWh respectively. This corresponds to a 16% and 27% reduction compared to the impacts of the baseline scenario of no recycling, which is consistent with the 20% to 30% saving for climate change value reported in Bonou et al. (2016), and 20% reported in Haapala and Prempreeda (2014). The 27% GHG reduction at recycling rate of 80 % from our study is, however, lower than the 65% reduction result reported at the same recycling rate by Wanga et al. (2019). This difference could be attributed to the fact that recycled contents were not considered in the latter case.

4.5.2. Scenario analysis

The role of transportation, and the total effect of the factors considered under the sensitivity analysis section above is analyzed here. For the combined effects of factors, best and worst combinations are investigated representing two outermost scenarios.

4.5.2.1. Transportation scenarios

Based on suppliers' information, wind turbines and most equipment of analyzed system are supplied from China, Spain and, France. Transportation distances were gathered based on suppliers' manufacturing sites. In section 4.1, we have seen that the contribution of transportation rages between 0.14% and 22 % of the total impacts, the lowest and the highest contribution occurring for metal depletion (MD) and photochemical oxidant formation (POF) impact category indicators. It is worth mentioning that more than 90% of the contribution was due to transporting of components and equipment from overseas. However, knowing who and where the suppliers are from will not be enough to determine the exact origin of a product in today's global market as a supplier from Europe, for example, may have subcontractors from China and vice versa. Therefore, the effects of distance on the baseline result were analyzed using three scenarios (SC1-SC3): SC 1 assumes that components and equipment of all wind farms came from Asia (China); SC 2 assumes that all components and equipment came from Europe (France), and SC 3 assumes that all components were manufactured in Ethiopia. SC 3 is more relevant and important to support local decision makers on future wind power development compared to currently operating wind farms, which are based on imported wind turbines.

Based on the data collection procedure followed for the baseline scenario, it is assumed that in SC 1 components and equipment were transported 11 640 km by ship and

1 602 km by lorry. In SC 2, transport distances are about 7 084 km and 924 km on sea and road respectively while SC 3 assumes 25 km road transport for Ashegoda wind farm and 100 km for Adam wind farms I and II to move components from nearby manufacturing facilities. For manufacturing of components and equipment, it is assumed that manufacturers in all scenarios receive raw materials from global markets and thus this distance was not separately modeled for sensitivity analysis. In addition, according to key assumptions stated in section 4.3.3, the electricity mixes of SC 1, SC 2 and SC 3 are adjusted for China, France, and Norway electricity (used as proxy for Ethiopia) mixes respectively.

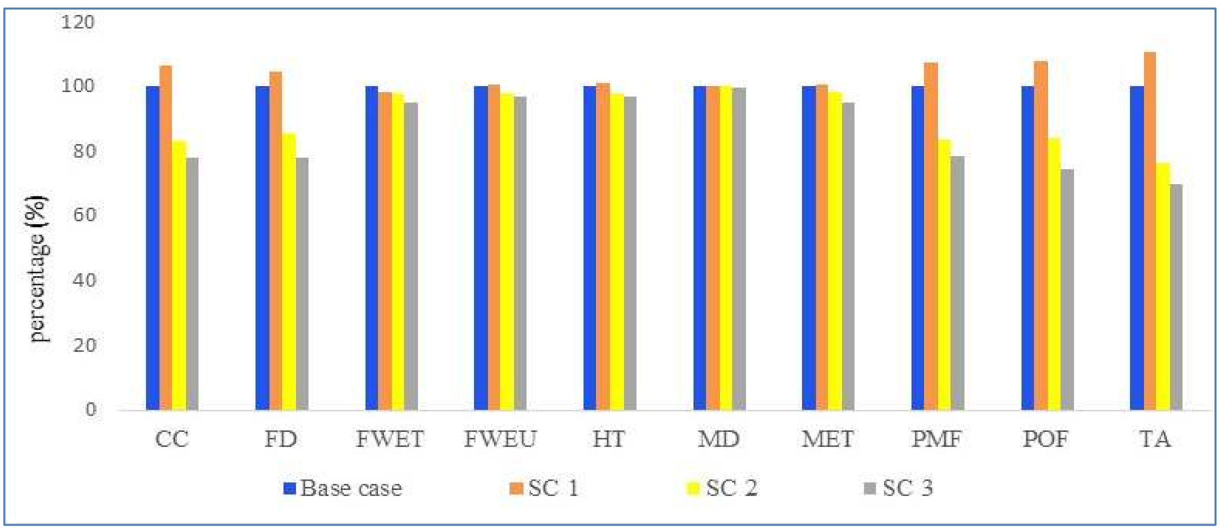


Figure 4.7 Comparison of the effects of transportation of component and parts on the LCA results of wind power system relative to base case

Figure 4.8 shows that freshwater ecotoxicity (FWET), freshwater eutrophication (FWEU), human toxicity (HT), metal depletion (MD), and marine ecotoxicity (MET) are less sensitive to changes in transportation distances compared to climate change (CC), fossil depletion (FD), particulate matter formation (PMF), photochemical oxidant formation (POF), and terrestrial acidification (TA). From section 4.4.1, the contribution of transportation is low in the first group of impact categories (i.e., FWET, FWEU, HT, MD, and

MET) compared to the second group of impacts (i.e., CC, FD, PMF, POF and TA). It follows that the higher the contribution of transportation in an impact category indicator the more sensitive it is to changes in transportation distances. SC 3 decreases impacts by 1% to 5% and by 22 to 30% in the first and second group of impact categories respectively, the highest change occurs at terrestrial acidification (TA). Similarly, SC 2 decreases impacts by 0.1% to 2%, and 14% to 24% in the first and second group of impacts categories respectively; still, the highest change happens in TA. On the other hand, SC 1 increases the impacts by 0.1% to 2%, and 5% to 11% in the first and second group of impact categories, where the lowest and highest increases occur in MD and TA. The relatively more significant changes in CC, FD, PMF, POF, and TA are related to emissions of fuel combustion.

4.5.2.2. 'Best Case' and Worst Case' scenarios

Although life cycle assessment of wind power systems offers insight into the potential environmental impacts, it may be difficult to model with certainty the lifespans, replacement of parts, energy production, transportation routes as well as the recycling of waste materials of wind farms. In section 4.5.1 above, we have examined the effect of individual assumptions on model results using sensitivity analysis. What if multiple assumptions are modeled as a group? Scenario analysis can be used to evaluate the 'best case' and 'worst case' scenarios established as a combination of individual assumptions affecting LCA model output. For this study, it is assumed that the 'best case' scenario will occur if a combination of a lifespan of 25 years, a recycling rate of 80%, estimated energy production data, and transportation data gathered by researchers are considered. Correspondingly, the 'worst case' assumes a combination of a lifespan of 15 years, metal scraps are landfilled, all components and parts manufactured and transported from a remote distance (in this case from China) and the LCA model is simulated based on actual energy produced data.

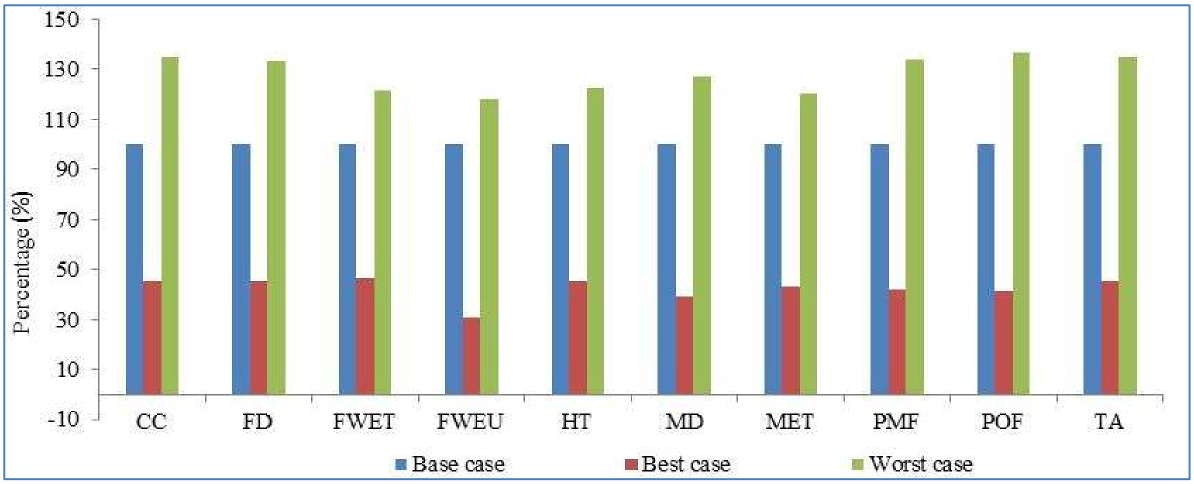


Figure 4.8 Senario analysis results of 'best case' and 'worst case' scenarios in comparsion to base case scenario. The 'best case' and 'wosrt case' scenarios were established by combining multiple assumptions and parameters.

Figure 4.9 presents the scenario analysis results for the 'best case' and 'worst case' scenarios compared to the base case scenario. In the 'best case' scenario, all impact categories show a reduction. For example, the GHG emission decreased to 15.72 g CO_2 eq. /kWh, which results in a 53 % decrease compared to the baseline scenario. On the other hand, the 'Worst Case' shows an increase in all impact categories. For instance, the GHG emission intensity increased to 47.75 g CO_2 eq. /kWh, which corresponds to a 42 % increase compared to the baseline case. Finally, if all components and parts are manufactured in Ethiopia and its electricity mix remains dependent on renewable sources as today, the GHG intensity of wind farms would further reduce to about 12.2. g CO_2 eq./kWh, which corresponds to a 64% reduction compared to the baseline scenario.

4.6. Conclusion and recommendation

The main objective of this LCA study was to estimate the environmental impacts of existing wind power system connected to the high voltage grid in Ethiopia. From the results obtained, the potential life cycle environmental impacts per 1 kWh electricity generated by the total system of three wind farms are: climate change:33.6 g CO_2 eq.; fossil depletion: 8 g oil eq., freshwater ecotoxicity: 0.023 g 1,4-DCB eq., freshwater eutrophication : 0.005 g N eq., human toxicity: 9.9 g 1,4-DCB eq., metal depletion: 18.7 g Fe eq., marine ecotoxicity: 0.098 g 1,4-DCB eq., particulate matter formation: 0.097g PM10 eq., photochemical oxidant formation: 0.144 g NMVOC eq., and terrestrial acidification: 0.21 g SO_2 eq. The pre-operation phase is the largest contributor to all the environmental impacts, with its share ranging between 82% and 96%. The cumulative energy demand and the energy return on investment (EROI) of the system are 0.339 MJ/kWh and 9.2 respectively.

The results of sensitivity and scenario analyses show that the LCA results would be affected by changing the wind plant lifespan, capacity factors, replacement rates of parts, transport routes, and waste management options. In general, this study would potentially give insight for developers and utility companies (operators) to pay proper attention to site selection, net power output estimation and proper maintenance in order to enhance production and reduce breakdowns. The end-of-life recycling benefits may trigger wind industry stakeholders including policy makers to work towards increased recycling of secondary materials generated at the end of life of wind power plants. More importantly, this study has the serves as an input to a comprehensive life cycle assessment database of the national energy system in Ethiopia together with the LCA done by the same authors on hydropower plants in the country (Teffera et al 2020). The results of this study should be interpreted within the context of the data limitations encountered during the course of the research, namely, lack of local datasets for electricity, transport and waste treatment activities relevant to local conditions. Future efforts in Ethiopia should, therefore, be dedicated to undertaking the creation of life cycle inventory databases with a focus on such background systems that will serve as a backbone for all kinds of LCAs in the country, and in and beyond the Horn of Africa region at large.

The environmental performance of the relatively cleaner power system supported by a comprehensive life cycle assessment such as this one can be used to support the development of communication tools such as environmental product declarations for export products on which Ethiopia and other countries in the region rely.

5. SYNTHESIS OF KEY RESULTS

This chapter compares and summaries key results from cases studies in chapter 3 and 4. At the beginning, it gives a short overview on the difficulties encountered during comparisons of LCAs and the rationale of this chapter. Next, it presents the simplified life cycle inventory (LCI) and life cycle impact assessment (LCIA) results of hydro and wind power schemes. Then, it discusses the contributions of life cycle stages, processes and elementary flows of each electricity generation technologies followed by short conclusion.

5.1. Background

Beside evaluation of environmental performance, LCA results can extend to compare different electricity technologies or sources. Wanga et al. (2019) suggest that factors such as installed capacities, system boundaries, lifespan, annual electricity production, location cause variations in LCA results of power systems. They recommend that the LCA results of different electricity generation technologies can be compared when the studies are conducted through the application of similar analytical structure, methods, assumptions and background data. In this study, the LCA models in both case studies are developed in line with the ISO 14040/44 standardized procedure. In addition, they share similar goal, system model approach, system boundaries in terms of life cycle stages, space and time, LCIA method and the same normalization basis. Although the two cases studies have used different baseline scenarios in terms of material recycling, the influence of recycling on the outputs has been checked in both cases using sensitivity analysis. For consistency, material recycling was not considered for this comparison. For other aspects related to methods and assumptions remain the same as chapter 3 and 4, they are not discussed here. Therefore, the comparison of Ethiopia's hydropower and wind power is enabled here with minimal difficulties that are commonly faced during comparison of studies due to different and unclear methodological choices and assumptions.

The main objective of this chapter is to provide a systematic comparison between hydro and wind power systems in order to recapitulate the last two chapters so that readers can see the two LCA results side by side. It gives a common background for 'hotspots' identification of analyzed systems using the 'Guide for interpreting LCA results' prepared by Zampori et al. (2016). By doing so, it facilitates analysis of stakeholders associated with the most relevant life cycle stages and processes identified that many LCA studies fail to cover.

5.2. Results and Discussion

5.2.1. Simplified LCI results

In this study, an aggregate LCI datasets were developed for hydro and wind power systems. Each consists of enormous number of flows from and to the environment. There are about 1351 and 1350 non-zero elementary flows for hydro and wind electricity generation technologies respectively, which is difficult to comprehend in terms of their sources and effects. Although a complete LCI was applied for the calculation of final LCIA results, it has been the interest of the researcher to present a simplified LCI data of this study. Therefore, the question is how to determine manageable, yet the most significant flows from total LCI datasets of the analyzed systems.

In order to reduce the scope and complexity of an analyzed system, with proper documentation, ISO 14040 allows cut-off for insignificant elements of the system (ISO, 2006a). The ISO 14044 suggests that percentage of total mass, total energy or total environmental impacts of the product system can be used as cut-off criteria (ISO, 2006b). It states that a material input can be cut-off if its contribution to the total mass or energy of a product system or its environmental significance in a given impact category is below a certain level. However, these ISO standards did not specify the threshold or cut-off criteria. According to EC-JRC (2010), a material contributing less than 5% of the total mass or energy of analyzed system can be omitted. In terms of environmental significance, LC stages, processes, materials or elementary flows that contribute less than 5% of a given impact indicator can be excluded from further analysis. The techniques such as sensitivity analysis can be used to evaluate the effects of cut-off (e.g., a material, process or a product input from analyzed system) on final outputs. However, since the total mass (energy) of a process or total environmental impacts of a product is not always known, the total mass or total environmental impact should be estimated or extrapolated using similar processes and expert judgment (ibid).

In reporting the aggregated LCI data, some researchers have used a cut-off criterion of 1% for elementary flows (Ribeiro and da Silva, 2010). However, it is difficult to know the impact of elementary flows solely based on their amount. First, a small amount of a certain substance may have a significant environmental impact in one or more impact categories than other substance with relatively larger quantity. Second, the same amount of different substances may have different levels of impacts. Third, the omission of an input or output flow from a process or product can be simulated and checked for its impact, but there is no means to check the effects of the omission of a flow from the LCI data. Therefore, it is difficult select significant flows from total LCI data applying the cut-off criteria

Table 5.1 presents some ‘common’ resources use and emissions to air, water, and soil environment resulting in a ‘‘simplified LCI’’. Some adjustments were made in naming of air emissions. Sulfur dioxide (SO_2) emissions were included as SOx values, where SO_2 accounts for more than 99% in both systems. Similarly, values of di-nitrogen monoxide (N_2O) were combined to the values of nitrogen oxides resulting in total NOx, where N_2O constitutes only 1 and 1.3% in NOx of hydro and wind power systems. The particulate emissions were consolidated in one indicator of ‘‘particulates’’. In addition, mass and volume units of energy resources were converted to energy unit ‘‘MJ’’, using the upper heating values.

Another important adjustment has been made on fossil and biogenic emissions of carbon dioxide (CO_2), carbon monoxide (CO) and methane (CH_4). The CO_2 emission in Table 5.1 contains the CO2 emissions from fossil and biogenic sources. The CO_2 emission from fossil covers for 9.2 and 98.9 % of total CO_2 emissions in hydro and wind power systems, respectively. Similarly, the CO and CH_4 emissions from fossil account for about 99.7 and 99.5 % and 0.5 and 99.2% of the total CO and CH_4 emissions of hydro and wind power, respectively. In hydroelectric reservoirs, the bacterial decomposition (aerobic and anaerobic) of organic matter is the main source of CO_2 and CH_4 (Rosa et al., 2004). Although the carbon has originated with natural sources, the emission of biogenic CO_2 and CH_4 from hydroelectric reservoirs are considered to have global warming impact equivalent to their counterpart emissions from fossil fuels. The results in Table 5.1 show that CO_2 and CH_4 emissions of hydropower are predominantly from biogenic sources (mainly from reservoirs) in contrast to CO_2 and CH_4 emissions of wind power where they are primarily from fossil combustion.

Table 5.1 Simplified LCI for hydro and wind power systems (Functional unit = 1kWh)

	Unit	Hydro	Wind
Natural resources consumption			
Gravel	g	9.01E+00	2.42E+01
Calcite	g	1.08E+00	3.62E+00
Iron ore	g	3.78E-01	3.93E+00
Clay, unspecified	g	1.87E-01	5.53E-01
Gypsum	g	6.33E-02	1.39E-01
Nitrogen	g	2.58E-02	2.72E-01
Carbon dioxide, in air	g	2.18E-02	3.69E-01
Nickel, 1.98% in silicates, 1.04% in crude ore	g	1.67E-02	2.55E-01
Bauxite, in ground	g	1.30E-02	7.71E-01
Oxygen	g	7.88E-03	8.34E-02
Chromium	g	5.98E-03	9.97E-02
Magnesite	g	4.10E-03	5.66E-02
Manganese	g	3.80E-03	4.96E-02
Salt	g	2.12E-03	2.43E-01
Aluminum	g	1.47E-03	8.77E-02
Sand	g	3.00E-05	8.69E-02
Emissions to air			
Carbon dioxide	g	3.98E+01	3.11E+01
Methane	g	1.28E+00	1.21E-01
SOx	g	1.09E-02	1.58E-01
Carbon monoxide	g	1.53E-02	1.52E-01
NOx	g	1.54E-02	1.03E-01
Particulates	g	4.51E-01	8.99E-02
NMVOC, unspecified origin	g	3.39E-03	2.66E-02
Arsenic	g	2.55E-06	4.16E-05
Cadmium	g	8.67E-07	1.36E-05
Chromium	g	2.09E-05	3.45E-04
Copper	g	8.70E-06	1.28E-04
Lead	g	8.49E-06	1.31E-04
Mercury	g	3.38E-07	5.19E-06
Nickel	g	7.92E-06	9.38E-05
Vanadium	g	8.58E-06	1.28E-05
Zinc	g	8.30E-06	1.38E-04

	Unit	Hydro	Wind
Discharges to water			
BOD5, Biological Oxygen Demand	g	1.61E-03	8.15E-03
COD, Chemical Oxygen Demand	g	1.62E-03	1.18E-02
DOC, Dissolved Organic Carbon	g	4.95E-04	4.88E-03
TOC, Total Organic Carbon	g	5.09E-04	4.67E-03
Solids, inorganic	g	2.03E-04	3.09E-03
Suspended solids, unspecified	g	3.99E-03	6.29E-02
Nitrate	g	9.98E-05	1.04E-02
Phosphate	g	8.83E-04	1.34E-02
Sulfate	g	1.06E-02	1.49E-01
Chloride	g	1.20E-02	2.53E-01
Oils, unspecified	g	4.40E-04	1.74E-03
Arsenic	g	1.06E-06	1.74E-05
Cadmium	g	1.49E-07	2.06E-06
Chromium	g	3.98E-07	5.22E-06
Chromium VI	g	1.41E-05	2.06E-04
Copper	g	7.74E-07	2.82E-05
Lead	g	5.02E-07	6.86E-06
Mercury	g	2.01E-08	2.43E-07
Nickel	g	1.25E-06	2.31E-05
Zinc	g	1.56E-05	1.75E-04
Non-material burdens (i.e. heat pollution)			
Heat, waste (to air)	kJ	1.73E-01	4.17E-01
Heat, waste (to water)	kJ	3.80E-04	7.64E-03
Land	m2	2.07E-03	6.00E-05
Water consumption			
Water, turbine use	m3	1.52E+00	1.26E-01
Water, consumptive use	m3	1.02E-03	1.25E-03
Primary energy resources consumption			
Crude oil	MJ	1.70E-02	2.83E-01
Hard coal	MJ	1.74E-02	8.10E-02
Brown coal (lignite)	MJ	4.40E-04	8.72E-03
Natural fuel gas	MJ	9.17E-03	2.93E-02

5.2.2. Environment impacts

Table 5.2 presents the environmental impacts of hydro and wind power systems. The impact of generating 1 kWh of electricity and supply to national grid has been calculated using ReCiPe 2008 midpoint (H) V1.10/World as the LCIA method. The results show that wind power has the higher environmental impact than hydropower in most impact categories, with exception of particulate matter formation (PMF), natural land transformation (NLT), and water depletion (WD). For instance, the climate change for the avenge wind power systems is 33.6 g CO_2 eq. and for hydropower system is 32.2 g CO_2 eq. per kWh generated. On the other hand, hydropower uses more land than wind farms due to the fact that hydropower plants large land requirements for reservoirs and workers' camps. Similarly, particulate matter formation (PMF) of hydropower is higher than wind power, which is due high amount of particulates are emitted during excavation for the construction of dams and power houses in hydropower plants.

After normalization analysis against World ReCiPe (H), ten impact category indicators are selected. These include climate change (CC), fossil depletion (FD), freshwater ecotoxicity (FWET), freshwater eutrophication (FWEU), human toxicity (HT), metal depletion (MD), marine ecotoxicity (MET), particulate matter formation (PMF), photochemical oxidant formation (POF) and terrestrial acidification (TA) and natural land transformation. Once selection of the most significant impact categories, the most relevant life cycle stages, processes and evaluated flows are determined based on their level of environmental significance, using the cut-off criteria suggested by Zampori et al. (2016).

Table 5.2 LCIA results of hydro and wind power systems in Ethiopia (per 1 kWh)

Impact category	Unit	Hydropower (a)	Wind power (b)	Ratio (b/a)
Climate change	g CO2 eq.	3.224E+01	3.359E+01	1.04
Ozone depletion	g CFC-11 eq.	1.557E-07	0.00E+00	0.00
Terrestrial acidification	g SO2 eq.	1.898E-02	2.133E-01	11.24
Freshwater eutrophication	g P eq.	2.927E-04	4.667E-03	15.94
Marine eutrophication	g N eq.	7.189E-04	7.333E-03	10.20
Human toxicity	g 1,4-DB eq.	6.084E-01	9.901E+00	16.27
Photochemical oxidant formation	g NMVOC eq.	3.329E-02	1.437E-01	4.32
Particulate matter formation	g PM10 eq.	1.492E-01	9.667E-02	0.65
Terrestrial ecotoxicity	g 1,4-DB eq.	2.772E-04	3.333E-03	12.02
Freshwater ecotoxicity	g 1,4-DB eq.	1.054E-03	2.367E-02	22.46
Marine ecotoxicity	g 1,4-DB eq.	6.877E-03	9.833E-02	14.30
Ionising radiation	kBq U235 eq.	1.154E-04	1.003E-03	8.69
Agricultural land occupation	m2a	4.542E-05	7.167E-04	15.78
Urban land occupation	m2a	2.106E-04	8.833E-04	4.19
Natural land transformation	m2	8.281E-04	1.438E-06	0.00
Water depletion	m3	1.523E+00	1.283E-01	0.08
Metal depletion	g Fe eq.	1.331E+00	1.873E+01	14.07
Fossil depletion	g oil eq.	8.410E-01	7.931E+00	9.43

Figure 5.1 presents the contribution of different life cycle stages in hydro and wind power systems. In the figure, one can see that the pre-operation phase is the largest contributor in all impacts of wind power and in most impact categories in hydropower. This is due to the fact that processes such as raw materials acquisition and manufacturing of components and products are lumped together in the construction and installation phase. In the case of hydropower, operation and maintenance phase accounts for about 90 and 100% in climate change and land use respectively, which is because of high GHG emissions from the hydroelectric reservoirs. In wind power, the overall land requirements during construction and installation phase (i.e., due to material and energy sources like gravel, coal, oil and gas) is almost offset by scrap concrete and residual material treatment, because it is assumed that waste concrete remains in the footings with no need of additional land for their disposal.

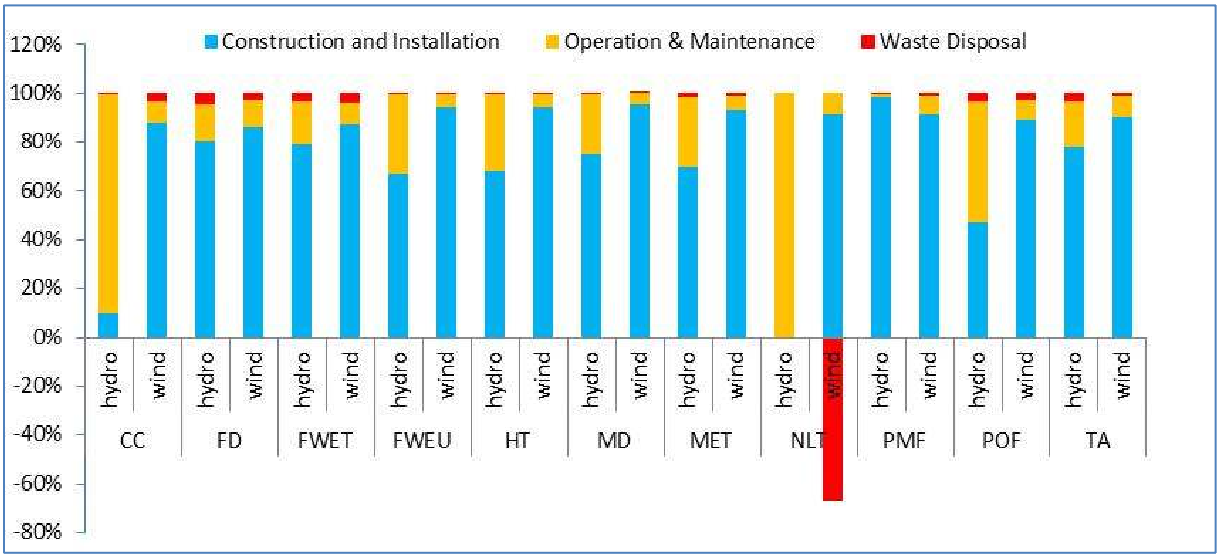


Figure 5.1 Percentage contributions of life cycle stages to selected environmental impacts

According to Zampori et al. (2016), all life cycle stages are considered most relevant if they contribute more than 80% to any impact categories before normalization and weighting. The same cut-off criteria apply for most relevant processes and elementary flows. **Tables 5.3** and **5.4** summarize the contribution of different life cycle stage processes and elementary flows to environmental impacts of hydro and wind power systems. Transparency is a key requirement in reporting LCA results. Tables 5.3 and 5.4 contain most relevant processes and elementary flows of analyzed systems and it is believed they increase clarity than plain word texts.

In **Table 5.3**, the main contributing pollutants for climate change are carbon dioxide (93%), followed by methane (4%) and di-nitrogen monoxide (N_2O) for hydropower. These gases are mostly released during operation phase associated to emissions from reservoirs and partly during cement manufacturing. However as shown in **Table 5.4**, although main emissions for climate change are still CO_2 (90%) and CH_4 ((%), many processes such as electricity generation, nylon 6-6 glass filled production, coal mining, iron production, cement production, transportation, waste treatment and heat production account for more than 77% of these gases for wind power the largest of which is from electricity generation. In both technologies/systems, fossil fuel depletion was mainly due to extraction of crude oil, hard coal and natural gas which are used at different processes such as electricity generation, diesel burning in machines, steel and coal production in the analyzed system.

The source of elementary flows (raw material extraction from and/or emissions to the environment) across the lifecycle stages has an impact on where to target strategies to optimize and reduce impacts on human health and the environment. The source of the emissions indicates whether the emissions are occurring at construction, operation or waste management stage. Unfortunately, indirect emissions from renewable electricity sources are less controllable from the perspective of individual power producers, compared to emissions generated directly at the power plant using fossil fuels. In general, elementary material and energy flows associated with construction and installation may be reduced or increased by extending or shortening the service period of a plant, while emission sources during operation can be targeted to achieve continuous improvement throughout the plant 's lifetime. For instance, selecting better materials (or suppliers) can reduce breakdown of units and the need for additional materials for replacements of components. On other hand, emissions such as turbine oils can be reduced through continuous inspection and maintenance.

Table 5.3 Most relevent contributions and hotspots to LCA of hydropower systems in Ethiopia

Impact category	Most relevant LC stages	Share (%)	Most relevant process	Share (%)	Most relevant elementary flow	Share (%)
CC	Pre-operation phase	9.8	GHG emissions from reservoirs	86	Carbon dioxide	93
	Operation & maintenance	89.8	Clicker production	3	Methane	4
	Waste disposal	0.4			Dinitrogen monoxide	1
		100		**89**		**98**
FD	Pre-operation phase	81	Electricity production from oil combustion	24	Crude oil extraction	46.7
	Operation & maintenance	15	Diesel burning in machines	21	Hard coal extraction	29.1
	Waste disposal	5	Low alloyed steel production	14	Natural gas extraction	24.1
			Reinforcing steel market	11		
			Hard coal mining	10		
		100		**80**		**99.9**
FWET	Pre-operation phase	79	Low-alloyed steel production	31	Bromine release into water bodies	49
	Operation & maintenance	17	Reinforcing steel market	19	Nickel release into water bodies	12
	Waste disposal	4	Electricity production from oil combustion	16	Copper release into water bodies	8
			Diesel burning in machines	9	Barium release into water bodies	4
			Copper production	6	Silver release into water bodies	4
					Zinc release into water bodies	3
		100		**81**		**83**
FWEU	Pre-operation phase	66.8	Copper production	46	Phosphate release to water bodies	99.5
	Operation & maintenance	32.6	Low-alloyed steel production	26	Phosphorus release water bodies	0.3
	Waste disposal	0.6	Coal waste treatment	10	Phosphorus emission into air	0.2
			Reinforcing steel market	10		
		100		**92**		**100**
HT	Pre-operation phase	68	Copper production	42.3	Arsenic emission to air	30
	Operation & maintenance	31.4	Low-alloyed steel production	24.8	Mercury emission to air	28
	Waste disposal	0.6	Reinforcing steel market	10.6	Lead emission to air	22
			Electricity production from oil combustion	7.1	Cadmium emission to air	7
					Vanadium emission to air	6
		100		**84.8**		**92**
MD	Pre-operation phase	75.2	Low-alloyed steel production	53	Iron extraction	29
	Operation & maintenance	24.3	Reinforcing steel market	26	Manganite extraction	25
	Waste disposal	0.5	Copper production	15	Copper extraction	14
					Nickel extraction	14

Impact category	Most relevant LC stages	Share (%)	Most relevant process	Share (%)	Most relevant elementary flow	Share (%)
					Chromium extraction	12
		100		**94**		**94**
MET	Pre-operation phase	70	Copper production	40	Copper emission into air	46
	Operation & maintenance	28	Electricity production from oil combustion	18	Nickel emission into air	13
	Waste disposal	2	Low-alloyed steel production	14	Vanadium emission into air	9
			Reinforcing steel market	7	Zinc emission into air	12
		100		**80**		**80**
TA	Pre-operation phase	78	Electricity production from oil combustion	**24**	Release of sulfur oxide (SO_2) into air	72
	Operation & maintenance	19	Diesel burning in building machine	**20**		
	Waste disposal	3	Low-alloyed steel production	12	Release of nitrogen oxides to air	26
			Clinker production	9		
			Reinforcing steel market	9		
			copper production	6		
			MV electricity market/supply	5		
		100		**83**		**98**
PMF	Pre-operation phase	98.3	Site excavation	94	Particulate >2.5µm and <10 µm	78
	Operation & maintenance	1.1			Particulate <2.5µm	19
	Waste disposal	0.5				
		100		**94**		**97**
POF	Pre-operation phase	47	Electricity production from oil combustion	31	Nitrogen oxides	46
	Operation & maintenance	49	Transportation	20	Methane, biogenic	39
	Waste disposal	3	Cement production	11	NMVOC emissions	10
			Burning of diesel in building machines	9		
			Low-alloyed steel production	7		
			Reinforcing steel market	6		
		100		**82**		**95**
NLT	Pre-operation phase	0.1	Land transformation from variety uses	99.97	Awash I, II and III HPPs	47
	Operation & maintenance	99.9			Amerti-Neshe HPP	21
	Waste disposal				Finchia HPP	11
					Tekeze HPP	9
					GG I and GG II HPPs	7
					Melka Wakena HPP	5
		100		**99.97**		**100**

Table 5.4 Most relevent contributions and hotspots to LCA of wind power systems in Ethiopia

Impact category	Most relevant LC stage	Share (%)	Most relevant process	Share (%)	Most relevant elementary flow	Share (%)
CC	Pre-operation phase	88	Electricity production	31.96	Carbon dioxide	90
	Operation & maintenance	9	Nylon 6-6 glass filled production	9.12	Methane	9
	Waste disposal	3	Coal mining	7.52		
			Pig iron production	9.10		
			Cement production	6.68		
			Transportation	5.61		
			Waste treatment	5.29		
			Heat production	2.39		
		100		**77.67**		**99**
FD	Pre-operation phase	86	Electricity production from oil combustion	24	Crude oil extraction	46.1
	Operation & maintenance	11	Diesel burning in machines	21	Hard coal extraction	29.4
	Waste disposal	3	Low alloyed steel production	14	Natural gas extraction	23.5
			Reinforcing steel market	11		
			Hard coal mining	10		
		100		**80**		**98.9**
FWET	Pre-operation phase	87	Low-alloyed steel production	31	Bromine release into water bodies	49
	Operation & maintenance	8	Reinforcing steel market	19	Release of nickel to water bodies	12
	Waste disposal	4	Electricity production from oil combustion	16	Copper release into water bodies	8
			Diesel burning in machines	9	Release of barium to water bodies	4
			Copper production	6	Release of silver into water bodies	4
					Zinc release into water bodies	3
		100		**81**		**80**
FWEU	Pre-operation phase	94.5	Sulfidic tailing treatment at mining	81	Phosphate release to water bodies	99.4
	Operation & maintenance	5.2	Coal & lignite spoil treatment at mining	13	Phosphorus release water bodies	0.3
	Waste disposal	0.3			Phosphorus release into air	0.3
		100		**94**		**100**
HT	Pre-operation phase	94.3	Copper production	51	Arsenic emission to air	30

	Operation & maintenance	5.4	Low-alloyed steel production	17	Mercury emission to air	28
	Waste disposal	0.4	Cast iron production	6	Lead emission to air	22
			Ferronickel production	4	Cadmium emission to air	6
			Sinter iron production	1	Vanadium emission to air	6
		100		**81**		**92**
MD	Pre-operation phase	94	Iron ore mining	22	Iron extraction	22
	Operation & maintenance	4	Manganese con. production	21	Manganite extraction	21
			Ferronickel production	18	Nickel extraction	18
			Chromium ore con. production	14	Chromium extraction	14
			Copper con. production	10	Copper extraction	11
		98		**84**		**85**
MET	Pre-operation phase	96	Primary copper production	57	Copper emission into air	55
	Operation & maintenance	4	Ferronickel, 25% production	9	Nickel emission into air	13
			Gold, from silver mine operation	3	Zinc emission into water	5
			Offshore well gas/oil production	3	Copper released into water	4
			Sea transportation	2	Zink released into air	4
			Low-alloyed steel production	2		
		100		**80**		**80**
TA	Pre-operation phase	90	Electricity production	43	SO_2 emission into air	72
	Operation & maintenance	9	Sea and road transportation	10	NO_x emissions into air	26
	Waste disposal	1	Primary copper production	9	Ammonia	1
			Nylon 6-6 glass-filled production	5		
			Hard coal production	4		
			Blasting	1		
			Clinker production	1		
			Coking	1		
			Heat production	1		
			Waste concrete treatment	1		
			Natural gas production	1		
		100		**81**		**100**
PMF	Pre-operation phase	91	Electricity production	34	Sulfur dioxide	32
	Operation & maintenance	7	Iron ore production	12	Particulate <2.5µm	24
	Waste disposal	1	Sea and road transportation	8	Nitrogen oxides	23
			Nylon 6-6 glass-filled production	4	Particulate >2.5µm & <10 µm	21
			Ferrochromium production	4		
			Primary copper production	3		
			Ferronickel, 25% Ni, production	2		
			Hard coal production	2		
			Sinter, iron production	2		

			Blasting	1		
			Clinker production	1		
			Coking	1		
			Diesel burning in building machines	1		
			Heat production	1		
			Waste concrete treatment	1		
		100		**80**		**100**
POF	Construction & installation	89	Electricity production	29	Nitrogen oxides into the air	69
	Operation & maintenance	8	Sea and road transportation	19	NMVOC emissions	15
	Waste disposal	3	Coking	9	Sulfur oxide	9
			Nylon 6-6 glass-filled production	5	Carbon monoxide	5
			Sinter, iron production	4	Methane, fossil	1
			Blasting	4		
			Clinker production	2		
			Diesel burning in building machines	2		
			Waste concrete treatment	2		
			Ferrochromium production	1		
			Hard coal production	1		
			Heat production	1		
			Iron ore production	1		
			Epoxy resin production	1		
			Natural gas production	1		
		100		**80**		**99**

5.3. Summary

The purpose of this chapter was to conduct a systematic comparison of the environmental loads and associated impacts across the entire lifecycle of hydro and wind power systems separately addressed in chapter 3 and 4. The results of the assessment show that the lifecycle of wind power generation has more impacts in most impact categories than hydropower generation, with exception particulate matter formation (PMF), natural land transformation (NLT) and water depletion. In many cases, a single impact category is caused by many processes associated to few lifecycle stages. Thus, the effort to minimize a given impact from processes require the involvement of many stakeholders including material producers (e.g., steel producers), energy providers, component and parts manufacturers, technology developers, plant contractors and operators, transport suppliers, and waste treatment operators.

In hydropower systems, the engagement of other sectors outside power sectors is also important. For instance, the soil and water conservation works are relevant to minimize GHG emissions from reservoirs of hydropower plants. Moreover, the academia and researchers play roles in conducting technology assessment. In general, the results indicate that reduction of environmental impacts in power generation involves the involvement of academia, LCA practitioners, developers, operators and high-level decision and policy makers.

6. CONCLUSIONS AND RECOMMENDATIONS

Life cycle assessment is useful in the analysis and making recommendations aimed at improving environmental performance of electricity generation systems. This chapter presents the conclusions, limitations and recommendations of this study. First, it reports the findings and draws conclusions based on the findings. Following this, it points out the limitations of the study. Finally, it makes recommendations relevant to researchers, developers, operators and policy makers of the power industry in general and Ethiopian electricity system in particular.

6.1. Conclusions

The potential environmental impacts of hydropower and wind power that represent almost 100% of current electricity generation system in Ethiopia were evaluated and compared for 2017 as reference year by life cycle assessment approach. Ten significant environmental impact indicators have been selected after normalization against world impact (H, A) values integrated in SimaPro version 8.0.1 Although natural land transformation (NLT) and freshwater ecotoxicity (FWET) were out of ten most relevant impacts for wind and hydro power systems respectively, they are included below for comparison purpose between hydro and wind power systems. The findings of the study show that:

1. The main life cycle environmental impacts of wind power per one kWh electricity generated are: Climate change: 33.6 g CO_2 eq., fossil depletion: 8 g oil eq., freshwater ecotoxicity: 0.024 g 1, 4-DCB eq., freshwater eutrophication: 0.005 g N eq., human toxicity: 9.9 g 1, 4-DCB eq., metal depletion: 18.7 g Fe eq., marine ecotoxicity: 0.098 g1,

4-DCB eq., natural land transformation: $1.4*10^{-6}$ m^2, particulate matter formation: 0.097 g PM10 eq., photochemical oxidant formation : 0.144 g NMVOC eq. and terrestrial acidification: 0.21 g SO_2 eq..

2. The main life cycle environmental impacts of hydropower per one kWh electricity generated are: Climate change: 32.24 g CO_2 eq., fossil depletion: 0.84 g oil eq., freshwater ecotoxicity: 0.001 g 1, 4-DCB eq., freshwater eutrophication: 0.0003 g P eq., human toxicity: 0.61 g 1, 4-DCB eq., metal depletion: 1.33 g Fe eq., marine ecotoxicity: 0.007 g 1, 4-DCB eq., natural land transformation: $8.3*10^{-4}$ m^2, particulate matter formation: 0.15 g PM10 eq., photochemical oxidant formation: 0.033 g NMVOC eq. and terrestrial acidification: 0.0184 g SO_2 eq..
3. Wind power has relatively higher environmental impacts than hydropower in most impact categories, except land use.
4. The pre-operation phase is the highest contributor in all impact categories of hydro and wind powers, with exception that the operation phase accounts for about 90% of climate change in hydropower systems. For hydropower, the pre-operation contributes between 62-99 %; where as in wind power its contribution ranges between 82 and 96%.
5. The sensitivity analyses show that the changes in lifespans, replacement rates, capacity factors (esp. in wind farms), transportation routes and material recycling rates significantly affect final results.
6. Most environmental impacts of hydro and wind power systems involve many processes across the supply chain. This demands the engagement of many stakeholders including academia, researchers, developers, operators and decision-and policy makers.

7. In general, this study serves as a good impetus for a comprehensive life cycle assessment database of the national energy system in Ethiopia which doesn't exist at the time of writing this thesis. More importantly, the environmental performance of the relatively cleaner power system supported by a comprehensive life cycle assessment such as this one can be used to support the development of communication tools such as environmental product declarations for export products on which Ethiopia and other countries in the region rely.

6.2. Limitations

Despite this study provides the life cycle assessment of hydro and wind power systems in Ethiopia for the first time that can serve as an input to a comprehensive life cycle assessment database of the national electricity system, the findings should be interpreted within the context of the data limitations particularly lack of local datasets for electricity, transport and waste treatment activities relevant to local conditions.

6.3. Recommendations

Hydro and wind power systems is expected remain the main clean energy technology in the electricity production mix of Ethiopia because of their relative high resource potential. Improving the environmental performance of electricity production will not only mitigate impacts of the power sector but will also present an opportunity to reduce impacts throughout the economy, for electricity is a critical input to other sectors. Based on the results of this research and the conclusions drawn above, following recommendations are suggested.

1. The study indicates that changes in factors like plant capacities, capacity factors, service periods, transportation distance and waste disposal options affect the environmental

impacts of the power systems. Therefore, developers and operators should properly consider these parameters from holistic perspectives. This may be achieved by integrating LCA during the design, development and operation activities.

2. In hydropower systems, decomposition of organic matters from reservoirs account for highest GHG emissions. Therefore, reservoirs areas should be properly cleared prior to filling and proper watershed management should be implemented around reservoirs to reduce decomposable organic matter.
3. The Bills of Materials (BoM) are considered as the heart of any manufacturing or construction processes. For this study, BoMs have been important data sources for the inventories of components, parts and materials of analyzed systems. However, three critical problems were faced: (i) the lack of details and a full description of some items; (ii) issues associated with language; and (iii) Lack of exchangeable file formats in the bill of quantities (BoM). The first limitation was observed mainly in generators, turbines, hydro-mechanical parts, transformers and overhead cranes (e.g., BoM of trolleys) in hydropower plants. The second problem was due to some elements of BoM were in languages where subassemblies or components have been imported. For instance, the penstocks, generators and gates of Koka hydropower plants are in Italian language and some elements BOM in Tis Abay II and Fincha Amerti-Neshe hydropower plants and Adama I and II wind farms are in Chinese languages where components and parts are imported. The third problem is even worse in terms of data exchangeability. The BoM of most components and parts in almost all power plants are in PDF format, which was difficult to extract data and information.

Efforts have been exerted to solve these limitations by using technical specifications of components and parts and experiences from other plants, personal communications to native speakers and language translation tools and through tedious manual efforts to extract necessary data and information into excel. Hence, the BOM should capture exact parts and materials with exact quantities in commonly used languages (e.g., English) and readable format so that the relevant inventory of input and output flows for the analyzed system can be established. Therefore, the operators (EEP and EEU) should have clear data management guidelines (framework) to control the completeness, language and file formatting of BOM so that they capture full data and information, and be readable and facilitate data exchange.

4. The availability of LCI datasets of background systems is a backbone for all kinds of LCAs (including energy systems) in the country. Future efforts in Ethiopia should, therefore, be dedicated to undertaking the creation of life cycle inventory databases with key background systems such as transport and waste management.
5. Finally, the electricity mix of Ethiopia is expected to expand and include other sources like solar, geothermal, biomass and fossil fuels like natural gas. Therefore, future LCA studies are important that considers future electricity generation scenarios.

7. References

ABB, 2003. Environmental Product Declaration: Power transformer 250 MVA. Registration number S-P- 00054. Legnano (Milano), Italy.

Abdallah, L., El-Shennawy, T., 2013. Reducing carbon dioxide emissions from electricity sector using smart electric grid applications. J. Eng. (United Kingdom) 2013. https://doi.org/10.1155/2013/845051

Abeliotis, K., Pactiti, D., 2014. Assessment of the Environmental Impacts of a Wind Farm in Central Greece during its Life Cycle. Int. J. Renew. Energy Res. 4, 1–6.

Ahmad, S., Tahar, R.M., 2014. Selection of renewable energy sources for sustainable development of electricity generation system using analytic hierarchy process: A case of Malaysia. Renew. Energy 63, 458–466. https://doi.org/10.1016/j.renene.2013.10.001

Al-Behadili, S.H., El-Osta, W.B., 2015. Life Cycle Assessment of Dernah (Libya) wind farm. Renew. Energy 83, 1227–1233. https://doi.org/10.1016/j.renene.2015.05.041

Amani, P., Schiefer, G., 2011. Review on suitability of available LCIA methodologies for assessing environmental impact of the food sector. Int. J. Food Syst. Dyn. 2, 194–206.

Amponsah, N.Y., Troldborg, M., Kington, B., Aalders, I., Hough, R.L., 2014. Greenhouse gas emissions from renewable energy sources: A review of lifecycle considerations. Renew. Sustain. Energy Rev. 39, 461–475. https://doi.org/10.1016/j.rser.2014.07.087

Aparecido, D., Silva, L., Oliveira, A., Moro, C., Aparecida, V., Shirosaki, L., Souza, M. De, 2019. Why using different Life Cycle Assessment software tools can generate different results for the same product system ? A cause – effect analysis of the problem. Sustain. Prod. Consum. 20, 304–315. https://doi.org/10.1016/j.spc.2019.07.005

Ardente, F., Beccali, M., Cellura, M., Lo Brano, V., 2008. Energy performances and life cycle assessment of an Italian wind farm. Renew. Sustain. Energy Rev. 12, 200–217. https://doi.org/10.1016/j.rser.2006.05.013

Arvesen, A., Hertwich, E.G., 2012. Assessing the life cycle environmental impacts of wind power: A review of present knowledge and research needs. Renew. Sustain. Energy

Rev. 16, 5994–6006. https://doi.org/10.1016/j.rser.2012.06.023
Asdrubali, F., Baldinelli, G., Alessandro, F.D., Scrucca, F., 2015a. Life cycle assessment of electricity production from renewable energies : Review and results harmonization. Renew. Sustain. Energy Rev. 42, 1113–1122. https://doi.org/10.1016/j.rser.2014.10.082
Asdrubali, F., Baldinelli, G., D'Alessandro, F., Scrucca, F., 2015b. Life cycle assessment of electricity production from renewable energies: Review and results harmonization. Renew. Sustain. Energy Rev. 42, 1113–1122. https://doi.org/10.1016/j.rser.2014.10.082
Asefa, M., Cao, M., He, Y., Mekonnen, E., Song, X., Jie, Y., 2020. Ethiopian vegetation types, climate and topography. Plant Divers. https://doi.org/10.1016/j.pld.2020.04.004
Asress, M.B., Simonovic, A., Komarov, D., Stupar, S., 2013. Wind energy resource development in Ethiopia as an alternative energy future beyond the dominant hydropower. Renew. Sustain. Energy Rev. 23, 366–378. https://doi.org/10.1016/j.rser.2013.02.047
Atallah, A.M., Bayoumi, E.M.A., 2015. Aggregating Large Wind Farm Composed of Different Smaller Wind Farms. Int. J. Power Eng. Energy 6, 551–559.
Atilgan, B., Azapagic, A., 2016. Renewable electricity in Turkey: Life cycle environmental impacts. Renew. Energy 89, 649–657. https://doi.org/10.1016/j.renene.2015.11.082
Awad, A., Yossof, I., 2016. Electricity production, economic growth and employment nexus in Sudan: A cointegration approach. Int. J. Energy Econ. Policy 6, 6–13.
Azeb, A., 2015. the Ethiopian Energy Sector-Investment Opportunities. Uk-Ethiopia Trade Invest. Forum 2015 24.
Bahati, G., 2011. Status of geothermal exploration and development in uganda. Short Course VI Explor. Geotherm. Resour. 1–10.
Bakken, T.H., Modahl, I.S., Engeland, K., Raadal, H.L., Arnøy, S., 2016. The life-cycle water footprint of two hydropower projects in Norway. J. Clean. Prod. 113, 241–250. https://doi.org/10.1016/j.jclepro.2015.12.036
Bao, Z., Zhang, S., Chen, Y., Liu, S., Zhang, Y., Wang, H., 2010. A review of material flow analysis. 2010 Int. Conf. Manag. Serv. Sci. MASS 2010. https://doi.org/10.1109/ICMSS.2010.5577113

Bare, J.C., Hofstetter, P., Pennington, D.W., de Haes, H.A.U., 2000. Midpoints versus endpoints: The sacrifices and benefits. Int. J. Life Cycle Assess. 5, 319–326. https://doi.org/10.1007/bf02978665

Barros, N., Cole, J.J., Tranvik, L.J., Prairie, Y.T., Bastviken, D., Huszar, V.L.M., Del Giorgio, P., Roland, F., 2011. Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude. Nat. Geosci. 4, 593–596. https://doi.org/10.1038/ngeo1211

Bekele, G., 2011. Feasibility Study of Solar-Wind Based Standalone Hybrid System for Application in Ethiopia. Proc. World Renew. Energy Congr. – Sweden, 8–13 May, 2011, Linköping, Sweden 57, 826–833. https://doi.org/10.3384/ecp11057826

Bekele, K., 2007. Life Cycle Assessment of Glove Leather in Elico-Gloving and Hide Unit. MSc Thesis, Addis Ababa University School of Graduate Studies, Addis Ababa, Ethiopia. Addis Ababa University.

Bellon-Maurel, V., Aissani, L., Bessou, C., Lardon, L., Loiseau, E., Risch, E., Roux, P., Junqua, G., 2013. What scientific issues in life cycle assessment applied to waste and biomass valorization? Editorial. Waste and Biomass Valorization 4, 377–383. https://doi.org/10.1007/s12649-012-9189-4

Bhat, V.I.K., Prakash, R., 2014. Life Cycle Analysis of Run-of River Small Hydro Power Plants in India. Open Renew. Energy J. 1, 11–16. https://doi.org/10.2174/1876387100901010011

Bjrklund, A.E., 2002. Survey of Approaches to Improve Reliability in LCA. Int J LCA 7 7, 64–72.

Boccard, N., 2009. Capacity factor of wind power realized values vs. estimates. Energy Policy 37, 2679–2688. https://doi.org/10.1016/j.enpol.2009.02.046

Bonou, A., Laurent, A., Olsen, S.I., 2016. Life cycle assessment of onshore and offshore wind energy-from theory to application. Appl. Energy 180, 327–337. https://doi.org/10.1016/j.apenergy.2016.07.058

Botelho, A., Ferreira, P., Lima, F., Pinto, L.M.C., Sousa, S., 2017. Assessment of the environmental impacts associated with hydropower. Renew. Sustain. Energy Rev. 70, 896–904. https://doi.org/10.1016/j.rser.2016.11.271

Bourgault, G., Lesage, P., Samson, R., 2012. Systematic disaggregation : a hybrid LCI computation algorithm enhancing interpretation phase in LCA. Int J Life Cycle Assess

17, 774–786. https://doi.org/10.1007/s11367-012-0418-7
Bozkurt, I., 2010. Energy Resources and Their Effects on Environment. WSEAS Trans. Environ. Dev. 6, 327–334.
Briones Hidrovo, A., Uche, J., Martínez-Gracia, A., 2017a. Accounting for GHG net reservoir emissions of hydropower in Ecuador. Renew. Energy 112, 209–221. https://doi.org/10.1016/j.renene.2017.05.047
Briones Hidrovo, A., Uche, J., Martínez-Gracia, A., 2017b. Accounting for GHG net reservoir emissions of hydropower in Ecuador. Renew. Energy. https://doi.org/10.1016/j.renene.2017.05.047
Brizmohun, R., Ramjeawon, T., Azapagic, A., 2015. Life cycle assessment of electricity generation in Mauritius. J. Clean. Prod. 106, 565–575. https://doi.org/10.1016/j.jclepro.2014.11.033
Bueno, C., Hauschild, M.Z., Rossignolo, J.A., Ometto, A.R., Mendes, N.C., 2016. Sensitivity analysis of the use of Life Cycle Impact Assessment methods: A case study on building materials. J. Clean. Prod. 112, 2208–2220. https://doi.org/10.1016/j.jclepro.2015.10.006
Burgess, A.A., Brennan, D.J., 2001. Application of life cycle assessment to chemical processes [WWW Document]. Chem. Eng. Sci. https://doi.org/10.1016/S0009-2509(00)00511-X
C.R.Kothari, 2004. Research Methodology - Methods and Techniques, Second rvised edition, New Delhi (India), New Age International (P) Limited, Publishers.
Carrascal, S.R., Pablo, 2014. Life Cycle Assessment - 1 Kwh generated by Gamesa G114-2.0MW On-shore wind farm 1.
Centre for Sustainable Energy(CSE), 2017. Common concerns about wind power, Second edi. ed. Centre for Sustainable Energy(CSE). https://doi.org/10.1074/jbc.M114.579185
Cetinay, H., Kuipers, F.A., Guven, A.N., 2017. Optimal siting and sizing of wind farms. Renew. Energy 101, 51–58. https://doi.org/10.1016/j.renene.2016.08.008
Chen, C., Habert, G., Bouzidi, Y., Jullien, A., Ventura, A., 2010. LCA allocation procedure used as an incitative method for waste recycling: An application to mineral additions in concrete. Resour. Conserv. Recycl. 54, 1231–1240.

https://doi.org/10.1016/j.resconrec.2010.04.001

Cheng, H., Yu, M., 2013. Effect of the transmission configuration of wind farms on their capacity factors. Energy Convers. Manag. 66, 326–335. https://doi.org/10.1016/j.enconman.2012.12.011

Cherubini, F., Bargigli, S., Ulgiati, S., 2009. Life cycle assessment (LCA) of waste management strategies: Landfilling, sorting plant and incineration. Energy 34, 2116–2123. https://doi.org/10.1016/j.energy.2008.08.023

Chevalier, B., Tatiana Reyes-Carrillo, B.L., 2011. methodology for choosing life cycle impact assessment sector-specific indicators, in: ICED 11-Impacting Society through Engineering Design, Vol. 5: Design for X / Design to X, Lyngby/Copenhagen, Denmark, 15.-19.08.2011. pp. 1563–1567. https://doi.org/10.1212/01.wnl.0000231514.33603.1e

Chipindula, J., Sai, V., Botlaguduru, V.V.S.V., Du, H., Kommalapati, R.R., Huque, Z., 2018. Life cycle environmental impact of onshore and offshore wind farms in Texas. Sustain. 10, 1–18. https://doi.org/10.3390/su10062022

Chris, H., Horvath, A., 1998. Economic Input-Output Models for Environmental Life-Cycle Assessment. POLICY Anal. 32.

Ciroth, A., 2012. Software for life cycle assessment, in: Life Cycle Assessment Handbook: A Guide for Environmentally Sustainable Products. p. 616.

Cole, P., Broderick, M., 2007. Environmental Impact Assessment (EIA) and Strategic Environmental Assessment (SEA): An exploration of synergies through development of a Strategic Environmental Framework (SEF). WIT Trans. Ecol. Environ. 102, 313–321. https://doi.org/10.2495/SDP070301

Crabtree, C.J., Zappalá, D., Hogg, S.I., 2015. Wind energy: UK experiences and offshore operational challenges. Proc. Inst. Mech. Eng. Part A J. Power Energy 229, 727–746. https://doi.org/10.1177/0957650915597560

Curran, M.A., 2015. Life Cycle Assessment Student Handbook. Wiley.

Curran, M.A., Mann, M., Norris, G., 2005. The international workshop on electricity data for life cycle inventories. J. Clean. Prod. 13, 853–862. https://doi.org/10.1016/j.jclepro.2002.03.001

D'Souza, N., Erhi Gbegbaje-Das, Shonfield, P., 2011. Life Cycle Assessment of Electricity

Production from a V112 Turbine Wind Plant. Vestas Wind Systems A/S.

Dametew, A.W., 2016. Design and Analysis of Small Hydro Power for Rural Electrification. Glob. J. Res. Eng. 16, 0975–5861.

DANIDA, 2016. Accelerating Wind Power Generation in Ethiopia: Thematic Programme Document. Ministry of Foreign Affairs, Royal Danish Embassy in Addis Ababa.

De Udo Haes, H.A., Heijungs, R., Suh, S., Huppes, G., 2004. Three strategies to overcome the limitations of life-cycle assessment. J. Ind. Ecol. 8, 19–32. https://doi.org/10.1162/1088198042442351

Deemer, B.R., Harrison, J.A., Li, S., Beaulieu, J.J., Delsontro, T., Barros, N., Bezerra-neto, J.F., Powers, S.M., Santos, M.A.D.O.S., Vonk, J.A., 2016. Greenhouse Gas Emissions from Reservoir Water Surfaces : A New Global Synthesis XX. https://doi.org/10.1093/biosci/biw117

Del Borghi, A., 2013. LCA and communication: Environmental Product Declaration. Int. J. Life Cycle Assess. 18, 293–295. https://doi.org/10.1007/s11367-012-0513-9

Demir, N., Akif Tas, K., 2013. Life cycle assessment of wind turbines in Pınarbas¸ ı-Kayseri. J. Clean. Prod. J. 54, 253–263.

Denholm, P., Kulcinski, G.L., 2004. Life cycle energy requirements and greenhouse gas emissions from large scale energy storage systems. Energy Convers. Manag. 45, 2153–2172. https://doi.org/10.1016/j.enconman.2003.10.014

Di, X., Nie, Z., Yuan, B., Zuo, T., 2007. Life Cycle Inventory for Electricity Generation in China. Int J LCA 12, 217–224.

Dinku, A., Adamu, A., Zerayohannes, G., 2002. Mix design proposal for structural concrete using messobo ordinary portland cement. Zede J. 19, 1–19.

Diriba;, D., Börner, J., 2015. Energy security, uncertainty, and energy resource use option in Ethiopia: A sector modelling approach. ZEF Discussion Papers on Development Policy, No. 201.

Earles, J.M., Halog, A., 2011. Consequential life cycle assessment : a review. https://doi.org/10.1007/s11367-011-0275-9

EC-JRC, 2019. Fossil CO2 and GHG emissions of all world countries. European Commission, Joint Research Centre, via E.Fermi 2147, 21027 Ispra (VA), Italy. https://doi.org/10.2760/687800

EC-JRC, 2018. Global Energy and Climate Outlook 2018 : Sectoral mitigation options towards a low-emissions economy. https://doi.org/10.2760/67475

EC-JRC, 2010. General guide for Life Cycle Assessment - Detailed guidance.First edition. EUR 24708 EN. Luxembourg. Luxembourg. https://doi.org/10.2788/38479

EDF Energy, 2009. Environmental Product Declaration of Electricity from Torness Nuclear Power Station Technical Report. Tech. Rep. 44.

EEP, 2017. Adama I Wind farm Project Summary Report.

Ekvall, T., Weidema, B.P., 2004. System Boundaries and Input Data in Consequential Life Cycle Inventory Analysis. Int J LCA 9, 161–171. https://doi.org/10.1065/lca2004.03.148

Elbatran, A.H., Abdel-Hamed, M.W., Yaakob, O.B., Ahmed, Y.M., Arif Ismail, M., 2015. Hydro power and turbine systems reviews. J. Teknol. 74, 83–90. https://doi.org/10.11113/jt.v74.4646

ENERGIE, 2001. Wind turbine grid connection and interaction.

Eshetu, H., 2010. Investigation and Analysis of Ashegoda Wind Farm Integration Impact on Ethiopian Grid. Master Thesis. Addis Ababa University.

European Commission -- Joint Research Centre -- Institute for Environment and Sustainability, 2010. International Reference Life Cycle Data System (ILCD) Handbook -- General guide for Life Cycle Assessment -- Detailed guidance. Constraints 417. https://doi.org/10.2788/38479

Fava, J.A., Page, A., 1992. Application of product life-cycle assessment to product stewardship and pollution prevention programs. Water Sci. Technol. 26, 275–287. https://doi.org/10.2166/wst.1992.0408

Fazzini, M., Bisci, C., Billi, P., 2015. The Climate of Ethiopia. World Geomorphol. Landscapes 65–87. https://doi.org/10.1007/978-94-017-8026-1

FDRE, 2019. Lighting to All: National Electrification Program 2 . 0. Integrated Planning for Universal Access.

FDRE, 2011a. Ethiopia's Climate-Resilient Green Economy - Green economy strategy.

FDRE, 2011b. Ethiopia's Climate Resilient Green Economy . Green Economy Strategy. Federal Democratic Republic of Ethiopia, Addis Ababa.

Feo, G. De, Malvano, C., 2009. The use of LCA in selecting the best MSW management system. Waste Manag. 29, 1901–1915. https://doi.org/10.1016/j.wasman.2008.12.021

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., 2009. Recent developments in Life Cycle Assessment. J. Environ. Manage. 91, 1–21. https://doi.org/10.1016/j.jenvman.2009.06.018

Finnveden, G., Moberg, Å., 2005. Environmental systems analysis tools - An overview. J. Clean. Prod. 13, 1165–1173. https://doi.org/10.1016/j.jclepro.2004.06.004

Finnvedena, G., Moberg, A., 2005. Environmental systems analysis tools e an overview. J. Clean. Prod. 13, 1165–1173.

Flury, K., Frischknecht, R., 2012. Life Cycle Inventories of Hydroelectric Power Generation.

Framework, A., 2016. Comparing Apples to Apples : Why the Net Energy Analysis Community Needs to Adopt the Life-Cycle Analysis Framework 1–15. https://doi.org/10.3390/en9110917

Frischknecht, R., 2010. LCI modelling approaches applied on recycling of materials in view of environmental sustainability, risk perception and eco-efficiency. Int. J. Life Cycle Assess. 15, 666–671. https://doi.org/10.1007/s11367-010-0201-6

Gagnon, L., Bélanger, C., Uchiyama, Y., 2002. Life-cycle assessment of electricity generation options: The status of research in year 2001. Energy Policy 30, 1267–1278. https://doi.org/10.1016/S0301-4215(02)00088-5

Gagnon, L., Van De Vate, J.F., 1997. Greenhouse gas emissions from hydropower: The state of research in 1996. Energy Policy 25, 7–13. https://doi.org/10.1016/S0301-4215(96)00125-5

Gallagher, J., Styles, D., McNabola, A., Williams, A.P., 2015. Current and future environmental balance of small-scale run-of-river hydropower. Environ. Sci. Technol. 49, 6344–6351. https://doi.org/10.1021/acs.est.5b00716

Gamesa, 2015. Environmental Product Declaration- Electricity from European GAMESA G132 - 5.0 MW offshore wind farm 1–33.

Garrett, P., Rønde, K., 2013. Life cycle assessment of wind power : comprehensive results from a state-of-the-art approach. Int J Life Cycle Assess 18, 37–48. https://doi.org/10.1007/s11367-012-0445-4

Geissler, S., Hagauer, D., Horst, A., Krause, M., Sutcliffe, P., 2013. Biomass Energy Strategy:

Ethiopia. Energy Dev. 41, 61476.

Geller, M.T.B., Meneses, A.A.D.M., 2016. Life cycle assessment of a small hydropower plant in the Brazilian amazon. J. Sustain. Dev. Energy, Water Environ. Syst. 4, 379–391. https://doi.org/10.13044/j.sdewes.2016.04.0029

Girma, Z., 2015. Techno-Economic Feasibility of Small Scale Hydropower in Ethiopia : The Case of the Kulfo River , in Southern Ethiopia. J. Renew. Energy 12.

Glassbrook, K.A., Carr, A.H., Drosnes, M.L., Oakley, T.R., Kamens, R.M., Gheewala, S.H., 2013. Energy for Sustainable Development Life cycle assessment and feasibility study of small wind power in Thailand. Energy Sustain. Dev. 8–15. https://doi.org/10.1016/j.esd.2013.12.004

Goedkoop, M., Heijungs, R., Huijbregts, M., Schryver, A. De, Struijs, J., Zelm, R. Van, 2008. ReCiPe 2008 - A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level, Ruimte en Milieu. https://doi.org/10.029/2003JD004283

Góralczyk, M., 2003. Life-cycle assessment in the renewable energy sector. Appl. Energy 75, 205–211. https://doi.org/10.1016/S0306-2619(03)00033-3

Grösser, S.N., Reyes-Lecuona, A., Granholm, G., 2017. Managing the Life Cycle to Reduce Environmental Impacts, in: Dynamics of Long-Life Assets: From Technology Adaptation to Upgrading the Business Model. pp. 1–356. https://doi.org/10.1007/978-3-319-45438-2

Güereca, L.P., Gassó, S., Baldasano, J.M., Jiménez-Guerrero, P., 2006. Life cycle assessment of two biowaste management systems for Barcelona, Spain. Resour. Conserv. Recycl. 49, 32–48. https://doi.org/10.1016/j.resconrec.2006.03.009

Guezuraga, B., Zauner, R., Pölz, W., 2012a. Life cycle assessment of two different 2 MW class wind turbines. Renew. Energy 37, 37–44. https://doi.org/10.1016/j.renene.2011.05.008

Guezuraga, B., Zauner, R., Pölz, W., 2012b. Life cycle assessment of two different 2 MW class wind turbines. Renew. Energy 37, 37–44. https://doi.org/10.1016/j.renene.2011.05.008

Guinée, J.B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T., Rydberg, T., 2011. Life cycle assessment: Past, present, and future. Environ. Sci.

Technol. 45, 90–96. https://doi.org/10.1021/es101316v

Gujba, H., Mulugetta, Y., Azapagic, A., 2011. Power generation scenarios for Nigeria: An environmental and cost assessment. Energy Policy 39, 968–980. https://doi.org/10.1016/j.enpol.2010.11.024

Günkaya, Z., Özdemir, A., Özkan, A., Banar, M., 2016. Environmental performance of electricity generation based on resources: A life cycle assessment case study in Turkey. Sustain. 8, 1–14. https://doi.org/10.3390/su8111097

Haapala, K.R., Prempreeda, P., 2014a. Comparative life cycle assessment of 2 . 0 MW wind turbines. Int. J. Sustain. Manuf. 3, 170–185.

Haapala, K.R., Prempreeda, P., 2014b. Comparative life cycle assessment of 2.0 MW wind turbines. Int. J. Sustain. Manuf. 3, 170. https://doi.org/10.1504/IJSM.2014.062496

Haapala, K.R., Rivera, J.L., Sutherland, J.W., 2008. Application of life cycle assessment tools to sustainable product design and manufacturing. Int. J. Innov. Comput. Inf. Control 4, 577–591.

Haas, G., Wetterich, F., Geier, U., 2000. Framework in Agriculture on the Farm Level. Int. J. Life Cycle Assess. 5, 345–348.

Haes, H.U. de, Heijungs, R., Huppes, G., Voet, E. van der, Hettelingh, J.-P., 2000. Full Mode and Attribution Mode in Environmental Analysis. J. Ind. Ecol. 4, 45–56.

Hanafi, J., Riman, A., 2015. Life cycle assessment of a mini hydro power plant in Indonesia: A case study in Karai River. Procedia CIRP 29, 444–449. https://doi.org/10.1016/j.procir.2015.02.160

Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I., 2018. Life Cycle Interpretation. In Life Cycle Assessment:Theory and Practice, pages 323-334. Springer International Publishing AG, Gewerbestrasse 11, 6330 Cham, Switzerland. https://doi.org/10.1007/978-3-319-56475-3

Heijungs, R., 1994. A generic method for the identification of options for cleaner products. Ecol. Econ. 10, 69–81. https://doi.org/10.1016/0921-8009(94)90038-8

Heijungs, R., Suh, S., 2002. The Computational Structure of Life Cycle Assessment. Eco-Efficiency in Industry and Science Volume 11. SPRINGER-SCIENCE+BUSINESS MEDIA, B.V. https://doi.org/https://doi.org/10.1007/978-94-015-9900-9_2

Henderson, P. a., 2018. Ecological effects of electricity generation, storage and use. CABI, UK.

Hendrickson, C.., Horvasth, A., Joshi, S., Klausner, M., Lave, L.B., McMicheal, F.C., 1997. Comparing two life cycle assessment approaches : A process model- vs economic input-output-based assessment. https://doi.org/10.1109/ISEE.1997.605313

Hendrickson, C., Horvath, A., Joshi, S., Lave, L., 1998. Economic input-output models for environmental life-cycle assessment. Environ. Sci. Technol. 32.

Hendrickson, C.T., Horvath, A., Joshi, S., Klausner, M., Lave, L.B., McMichael, F.C., 1997. Comparing two life cycle assessment approaches: a process model- vs. economic input-output-based assessment. IEEE Int. Symp. Electron. Environ. https://doi.org/10.1109/isee.1997.605313

Herrmann, I.T., Moltesen, A., 2014. Does it matter which Life Cycle Assessment (LCA) tool you choose ? e a comparative assessment of SimaPro and GaBi. J. Clean. Prod. 1, 1–7. https://doi.org/10.1016/j.jclepro.2014.08.004

Hertwich, E.G., 2013. Addressing biogenic greenhouse gas emissions from hydropower in LCA. Environ. Sci. Technol. 47, 9604–9611. https://doi.org/10.1021/es401820p

Hidrovo, A.., Uche, J., Martínez-Gracia, A., 2017. Accounting for GHG net reservoir emissions of hydropower in Ecuador. Renew. Energy 112, 209–221. https://doi.org/10.1016/j.renene.2017.05.047

Hischier, D., Group, E.P., Sciences, P., 2018. Current and future energy performance of power generation technologies in.

Hischier, R., Weidema, B., Althaus, H.-J., Bauer, C., Doka, G., Dones, R., Frischknecht, R., Hellweg, S., Humbert, S., Jungbluth, N., Köllner, T., Loerincik, Y., Margni, M., Nemecek, T., 2010. Swiss Centre for Life Cycle Inventories Implementation of Life Cycle Impact Assessment Methods.

Huang, C.L., Vause, J., Ma, H.W., Yu, C.P., 2012. Using material/substance flow analysis to support sustainable development assessment: A literature review and outlook. Resour. Conserv. Recycl. 68, 104–116. https://doi.org/10.1016/j.resconrec.2012.08.012

Hughes, G., 2012. The Performance of Wind Farms in the United Kingdom and Denmark. Renewable Energy Foundation (REF), London.

Huijbregts, M.A.J., Gilijamse, W., Ragas, A.M.J., Reijnders, L., 2003. Evaluating Uncertainty in Environmental Life-Cycle Assessment . A Case Study Comparing Two Insulation Options for a Dutch One-Family Dwelling. Environ. Sci. Technol. 37, 2600–2608.

Huntzinger, D.N., Eatmon, T.D., 2009. A life-cycle assessment of Portland cement manufacturing: comparing the traditional process with alternative technologies. J. Clean. Prod. 17, 668–675. https://doi.org/10.1016/j.jclepro.2008.04.007

Hydrochina Corporation, 2009. Fisibility study for Ethiopian Adama wind park.

IAEA, 1999. Health and environmental impacts of electricity generation systems : procedures for comparative assessment. International Atomic Energy Agency, 1999, Vienna., IAEA Bulletin.

IBERDROLA, 2018. Electricity from "Alto de la Degollllada" 50 MW on-shore wind farm. 48009 Bilbao (Vizcaya) - Spain.

IEA, 2020. Key World Energy Statistics 2020. International Energy Agency Website: iea.org. https://doi.org/10.1787/key_energ_stat-2014-en

IHA, 2019. Hydropower status report: Sector trends and insights. International Hydropower Association, London, United Kingdom. London, United Kigdom.

IPCC, 2011. IPCC, 2011: Summary for Policymakers. In: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation, Cambridge University Press. https://doi.org/10.5860/CHOICE.49-6309

Iraldo, F., Testa, F., Bartolozzi, I., 2014. An application of Life Cycle Assessment (LCA) as a green marketing tool for agricultural products: The case of extra-virgin olive oil in Val di Cornia, Italy. J. Environ. Plan. Manag. 57, 78–103. https://doi.org/10.1080/09640568.2012.735991

IRENA, 2019a. Renewable capacity statistics 2019, International Renewable Energy Agency (IRENA), Abu Dhabi, International Renewable Energy Agency (IRENA), Abu Dhabi.

IRENA, 2019b. Global energy transformation: A roadmap to 2050 (2019 edition), International Renewable Energy Agency, Abu Dhabi.

ISO, 2006a. Environmental management — Life cycle assessment — Principles and framework. Second edition, ISO 14040. Switzerland.

ISO, 2006b. Environmental management — Life cycle assessment — Requirements and guidelines, ISO 14044. https://doi.org/10.1007/s11367-011-0297-3

ISO, 2006c. 14040: Environmental management–life cycle assessment—Principles and framework. Int. Organ. Stand.

Jennifer DuBose, J., J David Frost, J., Chameau, J.-L.A., Vanegas, J.A., 1995. Sustainable Development and Technology. The Environmentally Educated Engineer - focuse on fundamentals, in: The Environmentally Educated Engineer - Focuse on Fundamentals. pp. 73–79. https://doi.org/10.1017/CBO9781107415324.004

Jolliet, O., Müller-wenk, R., Bare, J., Brent, A., Goedkoop, M., Heijungs, R., Itsubo, N., Peña, C., Pennington, D., Potting, J., Rebitzer, G., Stewart, M., 2004. The LCIA midpoint-damage framework of the UNEP / life cycle initiative UNEP / SETAC Life Cycle Initiative UNEP / SETAC Life Cycle Initiative The LCIA Midpoint-damage Framework of the UNEP / SETAC Life Cycle Initiative. https://doi.org/10.1007/BF02979083

Joshi, S., 1999. Product environmental life-cycle assessment using input-output techniques. J. Ind. Ecol. 3, 95–120. https://doi.org/10.1162/108819899569449

Kabayo, J., Marques, P., Garcia, R., Freire, F., 2019. Life-cycle sustainability assessment of key electricity generation systems in Portugal. Energy 176, 131–142. https://doi.org/10.1016/j.energy.2019.03.166

Kadiyala, A., Kommalapati, R., Huque, Z., 2017. Characterization of the life cycle greenhouse gas emissions from wind electricity generation systems. Int. J. Energy Environ. Eng. 8, 55–64. https://doi.org/10.1007/s40095-016-0221-5

Kadiyala, A., Kommalapati, R., Huque, Z., 2016. Evaluation of the life cycle greenhouse gas emissions from hydroelectricity generation systems. Sustain. 8, 1–14. https://doi.org/10.3390/su8060539

Kaldellis, J.K., Garakis, K., Kapsali, M., 2012. Noise impact assessment on the basis of onsite acoustic noise immission measurements for a representative wind farm. Renew. Energy 41, 306–314. https://doi.org/10.1016/j.renene.2011.11.009

Kaunda, C.S., Kimambo, C.Z., Nielsen, T.K., 2012. Hydropower in the Context of Sustainable Energy Supply: A Review of Technologies and Challenges. ISRN Renew. Energy 2012, 1–15. https://doi.org/10.5402/2012/730631

Kebede, S., 2012. Geothermal exploration and development in Ethiopia: status and future plan. Short Course VII Explor. Geotherm. Resour. 16.

Kenworthy, J.M., 1966. Temperature Conditions in the Tropical Highland Climates of East

Africa. East Afr. Geogr. Rev. 1–11.

Khan, R., 2015. Small Hydro Power in India: Is it a sustainable business? Appl. Energy 152, 207–216. https://doi.org/10.1016/j.apenergy.2014.11.063

Kim, S., Dale, B.E., 2005. Life Cycle Inventory Information of the United States Electricity System. Int J LCA 10, 294–304.

Kittner, N., Gheewala, S.H., Kammen, D.M., 2016. Energy return on investment (EROI) of mini-hydro and solar PV systems designed for a mini-grid. Renew. Energy 99, 410–419. https://doi.org/10.1016/j.renene.2016.07.023

Kitzes, J., 2013. An Introduction to Environmentally-Extended Input-Output Analysis. Resources 489–503. https://doi.org/10.3390/resources2040489

Kloepffer, W., 2008. Life cycle sustainability assessment of products (with Comments by Helias A. Udo de Haes, p. 95). Int. J. Life Cycle Assess. 13, 89–95. https://doi.org/10.1065/lca2008.02.376

Kubiszewski, I., Cleveland, C.J., Endres, P.K., 2010a. Meta-analysis of net energy return for wind power systems. Renew. Energy 35, 218–225. https://doi.org/10.1016/j.renene.2009.01.012

Kubiszewski, I., Cleveland, C.J., Endres, P.K., 2010b. Meta-analysis of net energy return for wind power systems. Renew. Energy 35, 218–225. https://doi.org/10.1016/j.renene.2009.01.012

Kuczenski, B., 2015. Partial ordering of life cycle inventory databases. Int J Life Cycle Assess. https://doi.org/10.1007/s11367-015-0972-x

Larrey-Lassalle, P., Catel, L., Roux, P., Rosenbaum, R.K., Lopez-Ferber, M., Junqua, G., Loiseau, E., 2017. An innovative implementation of LCA within the EIA procedure: Lessons learned from two Wastewater Treatment Plant case studies. Environ. Impact Assess. Rev. 63, 95–106. https://doi.org/10.1016/j.eiar.2016.12.004

Laurent, A., Espinosa, N., Hauschild, M.Z., 2018. LCA of Energy Systems. In Life Cycle Assessment: Theory and Practice, Life Cycle Assessment: Theory and Practice. https://doi.org/10.1007/978-3-319-56475-3

Lee, M., 2020. Review of the book: Environmental Assessment: The Regulation of Decision Making by Jane Holder. Environmental Values, Vol. 15, No. 1, pp. 129-132. URL: https://www.jstor.org/stable/30302074. Environ. Values 15, 129–132.

Leung, D.Y.C.C., Yang, Y., 2012. Wind energy development and its environmental impact: A review. Renew. Sustain. Energy Rev. 16, 1031–1039. https://doi.org/10.1016/j.rser.2011.09.024

Lewandowska, A., Foltynowicz, Z., 2004. New direction of development in environmental Life Cycle Assessment. Polish J. Environ. Stud. 13, 463–466.

Lindner, S., Legault, J., Guan, D., 2013. Disaggregating the Electricity Sector of China'S Input-Output Table for Improved Environmental Life-Cycle Assessment. Econ. Syst. Res. 25, 300–320. https://doi.org/10.1080/09535314.2012.746646

Liu, G., 2014. Development of a general sustainability indicator for renewable energy systems: A review. Renew. Sustain. Energy Rev. 31, 611–621. https://doi.org/10.1016/j.rser.2013.12.038

Louis, V.L. St., Kelly, C.A., Duchemin, É., Rudd, J.W.M., Rosenberg, D.M., 2013. Reservoir Surfaces as Sources of Greenhouse Gases to the Atmosphere : A Global Estimate 50, 766–775.

Lozano Miralles, J.A., López García, R., Palomar Carnicero, J.M., Martínez, F.J.R., 2020. Comparative study of heat pump system and biomass boiler system to a tertiary building using the Life Cycle Assessment (LCA). Renew. Energy 152, 1439–1450. https://doi.org/10.1016/j.renene.2019.12.148

Lund, C., Biswas, W., 2008. A Review of the Application of Lifecycle Analysis to Renewable Energy Systems. Bull. Sci. Technol. Soc. 28, 200–209. https://doi.org/10.1177/0270467608315920

Lund, H., Mathiesen, B.V., Christensen, P., 2010. Energy system analysis of marginal electricity supply in consequential LCA. https://doi.org/10.1007/s11367-010-0164-7

Magdalena, M., Kulczycka, J., 2020. The Identification of Hotspots in the Bioenergy Production Chain. Energies.

Mahmud, A.M., Kahsay, M.B., Hailesilasie, A., Hagos, F.Y., Gebray, P., Kelele, H.K., Gebrehiwot, K., Bauer, H., Deckers, S., De Baerdemaeker, J., Driesen, J., 2014. Solar energy resource assessment of the geba catchment, Northern Ethiopia. Energy Procedia 57, 1266–1274. https://doi.org/10.1016/j.egypro.2014.10.116

Maier, M., 2017. Towards a Spatio-temporal Life Cycle Analysis : a Novel Approach to

Consider Local and Regional Inventories. Doctoral Thesis, University of Exeter.
Majeau-Bettez, G., Strømman, A.H., Hertwich, E.G., 2011. Evaluation of Process- and Input – Output-based Life Cycle Inventory Data with Regard to Truncation and Aggregation Issues. Environ. Sci. Technol. 45, 10170–10177. https://doi.org/10.1021/es201308x
Mamani, R., Hackenberg, N., Hendrick, P., 2018. Efficiency of High Altitude On-shore Wind Turbines: Air Density and Turbulence Effects—Qollpana Wind Farm (Bolivia). Proceedings 2, 487. https://doi.org/10.3390/icem18-05385
Manuilova, A., Suebsiri, J., Wilson, M., 2009. Should Life Cycle Assessment be part of the Environmental Impact Assessment? Case study: EIA of CO2 Capture and Storage in Canada. Energy Procedia 1, 4511–4518. https://doi.org/10.1016/j.egypro.2009.02.269
Markandya, A., Wilkinson, P., 2007. Electricity generation and health. Lancet 370, 979–990. https://doi.org/10.1016/S0140-6736(07)61253-7
Martin, E.W., Chester, M. V, Vergara, S.E., 2015. Attributional and Consequential Life-cycle Assessment in Biofuels : a Review of Recent Literature in the Context of System Boundaries 82–89. https://doi.org/10.1007/s40518-015-0034-9
Martínez, E., Sanz, F., Pellegrini, S., Jiménez, E., Blanco, J., 2009. Life-cycle assessment of a 2-MW rated power wind turbine: CML method. Int. J. Life Cycle Assess. 14, 52–63. https://doi.org/10.1007/s11367-008-0033-9
Masanet, E., Chang, Y., Gopal, A.R., Larsen, P., Morrow, W.R., Sathre, R., Shehabi, A., Zhai, P., 2013. Life-Cycle Assessment of Electric Power Systems. Annu. Rev. Environ. Resour. 38, 107–136. https://doi.org/10.1146/annurev-environ-010710-100408
Matthews, H.S., Small, M.J., 2001. Extending the Boundaries of Life-Cycle Assessment through Environmental Economic Input-Output Models 4, 7–10.
May, J.R., Brennan, D.J., 2003. Application of data quality assessment methods to an LCA of electricity generation. Int. J. Life Cycle Assess. 8, 215–225. https://doi.org/10.1007/BF02978474
Mekonnen, M.M., Hoekstra, A.Y., 2012. The blue water footprint of electricity from hydropower. Hydrol. Earth Syst. Sci. 16, 179–187. https://doi.org/10.5194/hess-16-179-2012
Menoufi, K.A.I., 2011. Life Cycle Analysis and Life Cycle Impact Assessment

methodologies: State of the art, Master Thesis.
MoFED, 2010. Growth and Transformation Plan 2010/ 11 -20 14/ 15. Volume I: Main Text. Ministry or Finance and Economic Development November2010. Federal Democratic Republic of Ethiopia Growth. Addis Ababa. https://doi.org/10.1049/oap-cired.2017.1227
Mondal, A.H., Bryan, E., Ringler, C., Rosegrant, M., 2017. Ethiopian power sector development : Renewable based universal electricity access and export strategies. Renew. Sustain. Energy Rev. 75, 11–20. https://doi.org/10.1016/j.rser.2016.10.041
Mondal, M.A.H., Bryan, E., Ringler, C., Mekonnen, D., Rosegrant, M., 2018. Ethiopian energy status and demand scenarios: Prospects to improve energy efficiency and mitigate GHG emissions. Energy 149, 161–172. https://doi.org/10.1016/j.energy.2018.02.067
Morero, B., Rodriguez, M.B., Campanella, E.A., 2015. Environmental impact assessment as a complement of life cycle assessment. Case study: Upgrading of biogas. Bioresour. Technol. 190, 402–407. https://doi.org/10.1016/j.biortech.2015.04.091
Morrison-Saunders, A., Fischer, T.B., 2006. What is wrong with EIA and SEA anyway? A sceptic's perspective on sustainability assessment. J. Environ. Assess. Policy Manag. 8, 19–39. https://doi.org/10.1142/S1464333206002372
MoWE, 2012a. Scaling - Up Renewable Energy Program Ethiopia Investment Plan. Ministry of Water and Energy,Federal Democratic Republic of Ethiopia, Addis Ababa, Ethiopia. Addis Ababa.
MoWE, 2012b. Ethiopian National Energy Policy. Minstry of Water and Energy, Addis Ababa, Ethiopia. https://doi.org/10.1049/oap-cired.2017.1227
Mulugeta, D., Weijun, D., Zhao, J.H., 2015. Hydropower for sustainable water and energy development in Ethiopia. Sustain. Water Resour. Manag. 1, 305–314. https://doi.org/10.1007/s40899-015-0029-0
Mulugetta, Y., 2007. Renewable energy technology and implementation mechanisms for ethiopia. Energy Sources, Part B Econ. Plan. Policy 2, 3–17. https://doi.org/10.1080/15567240600629104
Mulugetta, Y., 1999. Energy in rural Ethiopia: Consumption patterns, associated problems, and prospects for a sustainable energy strategy. Energy Sources 21, 527–539. https://doi.org/10.1080/00908319950014650

Murphy, D.J., Carbajales-Dale, M., Moeller, D., 2016. Comparing apples to apples: Why the net energy analysis community needs to adopt the life cycle analysis framework. Energies 9, 1–15. https://doi.org/10.3390/en9110917

Murphy, R., 2016. Interpreting Life Cycle Assessment for Decision-Making on Emerging Materials. PhD dissertation. National Physical Laboratory, University of Surrey, UK. University of Surrey.

National Planning Commission, 2016. Growth and Transformation Plan II (GTP II) (2016-2020). National Planning Commission of Federal Democratic Republic of Ethiopia, Addis Ababa. National Planning Commission, Addis Ababa.

Navarro-Pineda, F.S., R.Handler, C.Sacramento-Rivero, J., 2017. Potential effects of the Mexican energy reform on life cycle impacts of electricity generation in Mexico and the Yucatan region. J. Clean. Prod. 164, 1016–1025. https://doi.org/10.1016/j.jclepro.2017.07.023

Nemecek, T., Dubois, D., Huguenin-Elie, O., Gaillard, G., 2011. Life cycle assessment of Swiss farming systems: I. Integrated and organic farming. Agric. Syst. 104, 217–232. https://doi.org/10.1016/j.agsy.2010.10.002

Nigussie, T., Bogale, W., Bekele, F., Dribssa, E., 2017. Feasibility study for power generation using off- grid energy system from micro hydro-PV-diesel generator-battery for rural area of Ethiopia: The case of Melkey Hera village, Western Ethiopia. AIMS Energy 5, 667–690. https://doi.org/10.3934/energy.2017.4.667

NPC, 2016. Growth and Transformation Plan II (GTP II) (2015/16-2019/20) - Volume I: Main Text. National Planning Commission, Federal Democratic Republic of Ethiopia, Addis Ababa.

Ocampo, L., Carreon, R., Carvajal, J.A., Galagar, K.J., Gialolo, D.M., Gulayan, M., Indig, D., Nuñez, D.M., Tagsip, W.C., Vallecera, J.M., Villegas, Z., 2015. Matrix-based life cycle assessment (MLCA) on polystyrene and recycled paper egg tray packaging. J. Prod. Eng. 18.

Olivier, J.G.J., Peters, J.A.H.W., 2020. Trends in Global CO2 and Total Greenhouse Gas Emissions:Report 2019. PBL Netherlands Environmental Assessment Agency The Hague.

Ozoemena, M., Cheung, W.M., Hasan, R., 2018. Comparative LCA of technology improvement opportunities for a 1 . 5 - MW wind turbine in the context of an onshore wind farm International Organisation for Standardisation. Clean Technol. Environ. Policy. https://doi.org/10.1007/s10098-017-1466-2

Pang, M., Zhang, L., Wang, C., Liu, G., 2015. Environmental life cycle assessment of a small hydropower plant in China. Int. J. Life Cycle Assess. 20, 796–806. https://doi.org/10.1007/s11367-015-0878-7

Papageorgiou, L.G., 2009. Supply chain optimisation for the process industries: Advances and opportunities. Comput. Chem. Eng. 33, 1931–1938. https://doi.org/10.1016/j.compchemeng.2009.06.014

Park, E., Yoo, S., Lee, S., Li, H., 2014. Accelerating graph computation with racetrack memory and pointer-assisted graph representation. Proc. -Design, Autom. Test Eur. DATE. KTH School. https://doi.org/10.7873/DATE2014.172

Paulillo, A., Striolo, A., Lettieri, P., 2019. The environmental impacts and the carbon intensity of geothermal energy: A case study on the Hellisheiði plant. Environ. Int. 133, 105226. https://doi.org/10.1016/j.envint.2019.105226

Peters, G.P., 2007. Efficient Algorithms for Life Cycle Assessment , Input-Output Analysis , and Monte-Carlo Analysis. Int J LCA 12, 373–380.

Polinder, H., Pijl, F.F.A. van der, Vilder, G.-J. de, Tavner, P., 2005. Comparison of Direct-Drive and Geared Generator Concepts for Wind Turbines. IEEE Int. Conf. Electr. Mach. Drives 543–550. https://doi.org/10.1109/TEC.2006.875476

Polinder, H., Van Der Pijl, F.F.A., De Vilder, G.J., Tavner, P.J., 2006. Comparison of direct-drive and geared generator concepts for wind turbines. IEEE Trans. Energy Convers. 21, 725–733. https://doi.org/10.1109/TEC.2006.875476

PRé, 2018. SimaPro Database Manual Methods Library. https://doi.org/10.1017/CBO9781107415324.004

Psomopoulos, C.S., Kalkanis, K., Kaminaris, S., Ioannidis, G.C., Pachos, P., 2019. A Review of the Potential for the Recovery of Wind Turbine Blade Waste Materials. Recycling 4, 1–9. https://doi.org/10.3390/recycling4010007

Qinfen Zhang; Bryan Karney, M.A., Heather L. MacLean, M.A., Feng, ; Jingchun, 2007. Life-Cycle Inventory of Energy Use and Greenhouse Gas Emissions for Two Hydropower Projects in China. J. Infrastruct. Syst. 13, 271–279.

https://doi.org/10.1061/(ASCE)1076-0342(2007)13
Raadal, H.L., Gagnon, L., Modahl, I.S., Hanssen, O.J., 2011a. Life cycle greenhouse gas (GHG) emissions from the generation of wind and hydro power. Renew. Sustain. Energy Rev. 15, 3417–3422. https://doi.org/10.1016/j.rser.2011.05.001
Raadal, H.L., Gagnon, L., Modahl, I.S., Hanssen, O.J., Raadala, H.L., Gagnonb, L., Modahla, I.S., Hanssena, O.J., 2011b. Life cycle greenhouse gas (GHG) emissions from the generation of wind and hydro power. Renew. Sustain. Energy Rev. 15, 3417–3422. https://doi.org/10.1016/j.rser.2011.05.001
Raadala, H.L., Gagnonb, L., Modahla, I.S., Hanssena, O.J., 2011. Life cycle greenhouse gas (GHG) emissions from the generation of wind and hydro power. Renew. Sustain. Energy Rev. 15, 3417–3422. https://doi.org/10.1016/j.rser.2011.05.001
Ram, M., Aghahosseini, A., Breyer, C., 2020. Job creation during the global energy transition towards 100% renewable power system by 2050. Technol. Forecast. Soc. Change 151, 119682. https://doi.org/10.1016/j.techfore.2019.06.008
Raugei, M., Leccisi, E., 2016. A comprehensive assessment of the energy performance of the full range of electricity generation technologies deployed in the United Kingdom. Energy Policy 90, 46–59. https://doi.org/10.1016/j.enpol.2015.12.011
Rehl, T., Lansche, J., Müller, J., 2012. Life cycle assessment of energy generation from biogas — Attributional vs . consequential approach. Renew. Sustain. Energy Rev. 16, 3766–3775. https://doi.org/10.1016/j.rser.2012.02.072
Ribeiro, F. de M., da Silva, G.A., 2010. Life-cycle inventory for hydroelectric generation: a Brazilian case study. J. Clean. Prod. 18, 44–54. https://doi.org/10.1016/j.jclepro.2009.09.006
Rosa, L.P., Dos Santos, M.A., Matvienko, B., Dos Santos, E.O., Sikar, E., 2004. Greenhouse gas emissions from hydroelectric reservoirs in tropical regions. Clim. Change 66, 9–21. https://doi.org/10.1023/B:CLIM.0000043158.52222.ee
Rosenbaum, R.K., 2017. Selection of Impact Categories, Category Indicators and Characterization Models in Goal and Scope Definition. https://doi.org/10.1007/978-94-024-0855-3_2
Ross, S., Evans, D., 2002. Use of life cycle assessment in environmental management. Environ. Manage. 29, 132–142. https://doi.org/10.1007/s00267-001-0046-7

Ruviaro, C.F., Gianezini, M., Brandão, F.S., Winck, C.A., Dewes, H., 2012. Life cycle assessment in Brazilian agriculture facing worldwide trends. J. Clean. Prod. 28, 9–24. https://doi.org/10.1016/j.jclepro.2011.10.015

Sad, N., 2015. A Framework for Energy Use Indicators and Their Reporting in Life Cycle Assessment 12, 429–436. https://doi.org/10.1002/ieam.1735

Sahle, A., Potting, J., 2013. Environmental life cycle assessment of Ethiopian rose cultivation. Sci. Total Environ. 443, 163–172. https://doi.org/10.1016/j.scitotenv.2012.10.048

Saidur, R., Rahim, N.A., Islam, M.R., Solangi, K.H., 2011. Environmental impact of wind energy. Renew. Sustain. Energy Rev. 15, 2423–2430. https://doi.org/10.1016/j.rser.2011.02.024

Santoyo-Castelazo, E., Gujba, H., Azapagic, A., 2011. Life cycle assessment of electricity generation in Mexico. Energy 36, 1488–1499. https://doi.org/10.1016/j.energy.2011.01.018

Schreiber, A., Marx, J., Zapp, P., 2019. Comparative life cycle assessment of electricity generation by different wind turbine types. J. Clean. Prod. 233, 561–572. https://doi.org/10.1016/j.jclepro.2019.06.058

Scion, N.B., Scion, W.J., 2007. The Role of LCA in Decision Making in the Context of Sustainable Development.

Seto, K.E., Panesar, D.K., Churchill, C.J., 2017. Criteria for the evaluation of life cycle assessment software packages and life cycle inventory data with application to concrete. Int. J. Life Cycle Assess. 22, 694–706. https://doi.org/10.1007/s11367-016-1060-6

Shahbaz, M., Tang, C.F., Shahbaz Shabbir, M., 2011. Electricity consumption and economic growth nexus in Portugal using cointegration and causality approaches. Energy Policy 39, 3529–3536. https://doi.org/10.1016/j.enpol.2011.03.052

Shmatko, N., Volkova, G., 2017. Service or Devotion ? Motivation Patterns of Russian Researchers. Foresight STI Gov. 11, 54–66. https://doi.org/10.17323/2500-2597.2017.1.54.66

Simões, C.L., Costa Pinto, L.M., Simoes, R., Bernardo, C.A., 2013. Integrating environmental and economic life cycle analysis in product development: A material selection case study. Int. J. Life Cycle Assess. 18, 1734–1746. https://doi.org/10.1007/s11367-013-0561-9

Skone, T.J., Littlefield, J., Eckard, R., Cooney, G., Marriott, J., 2012. Role of Alternative Energy Sources : Hydropower Technology Assessment.

Soe, T.T., Zheng, M., Aung, Z.N., 2015. Assessment of Economic Feasibility on Promising Wind Energy Sites in Myanmar. Int. J. Renew. Energy Res. 5, 699–707.

Song, Q., Wang, Z., Li, J., 2013. Environmental performance of municipal solid waste strategies based on LCA method: A case study of Macau. J. Clean. Prod. 57, 92–100. https://doi.org/10.1016/j.jclepro.2013.04.042

Speck, B.R., Selke, S., Auras, R., Fitzsimmons, J., 2015. Choice of Life Cycle Assessment Software Can Impact Packaging System Decisions. Packag. Technol. Sci. 579–588. https://doi.org/10.1002/pts

Starkey, R., 1998. Environmental Management Tools for SMEs : A Handbook. Denmark.

Steeneveld GJ, E.B., 2014. Analysing the Impact of Topography on Precipitation and Flooding on the Ethiopian Highlands. J. Geol. Geosci. 03. https://doi.org/10.4172/2329-6755.1000173

Styles, D., Gibbons, J., Williams, A.P., Dauber, J., 2015. Consequential life cycle assessment of biogas , biofuel and biomass energy options within an arable crop rotation 1305–1320. https://doi.org/10.1111/gcbb.12246

Suh, S., Huppes, G., 2005. Methods for life cycle inventory of a product. J. Clean. Prod. 13, 687–697. https://doi.org/10.1016/j.jclepro.2003.04.001

Suksuntornsiri, P., Limmeechokchai, B., 2005. The PCA and IOA approaches for life-cycle analysis of greenhouse gas emissions from Thai commodities and energy consumption. Songklanakarin J. Sci. Technol. 27, 177–189.

Suwanit, W., Gheewala, S.H., 2011. Life cycle assessment of mini-hydropower plants in Thailand. Int. J. Life Cycle Assess. 16, 849–858. https://doi.org/10.1007/s11367-011-0311-9

Tadesse, K., 2014. Wind Resource Assessment at Adama II Wind Farm Using WAsP. Addis Ababa University.

Tillman, A., 2000. Significance of decision-making for LCA methodology. Environ. Impact Assess. Rev. 20, 113–123.

Tkáč, Š., 2018. Hydro power plants, an overview of the current types and technology. Sel. Sci. Pap. - J. Civ. Eng. 13, 115–126. https://doi.org/10.1515/sspjce-2018-0011

Tremeac, B., Meunier, F., 2009. Life cycle analysis of 4.5 MW and 250 W wind turbines. Renew. Sustain. Energy Rev. 13, 2104–2110. https://doi.org/10.1016/j.rser.2009.01.001

Treyer, K., Bauer, C., 2016a. Life cycle inventories of electricity generation and power supply in version 3 of the ecoinvent database—part II: electricity markets. Int. J. Life Cycle Assess. 21, 1255–1268. https://doi.org/10.1007/s11367-013-0694-x

Treyer, K., Bauer, C., 2016b. Life cycle inventories of electricity generation and power supply in version 3 of the ecoinvent database—part I: electricity generation. Int. J. Life Cycle Assess. 21, 1236–1254. https://doi.org/10.1007/s11367-013-0665-2

Treyer, K., Bauer, C., 2013. Life cycle inventories of electricity generation and power supply in version 3 of the ecoinvent database — part I : electricity generation 3. https://doi.org/10.1007/s11367-013-0665-2

Tucho, G.T., Weesie, P.D.M., Nonhebel, S., 2014. Assessment of renewable energy resources potential for large scale and standalone applications in Ethiopia. Renew. Sustain. Energy Rev. 40, 422–431. https://doi.org/10.1016/j.rser.2014.07.167

Turconi, R., Boldrin, A., Astrup, T., 2013a. Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations. Renew. Sustain. Energy Rev. 28, 555–565. https://doi.org/10.1016/j.rser.2013.08.013

Turconi, R., Boldrin, A., Astrup, T., 2013b. Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations. Renew. Sustain. Energy Rev. 28, 555–565. https://doi.org/10.1016/j.rser.2013.08.013

Turner, D.A., Williams, I.D., Kemp, S., 2016. Combined material flow analysis and life cycle assessment as a support tool for solid waste management decision making. J. Clean. Prod. 129, 234–248. https://doi.org/10.1016/j.jclepro.2016.04.077

UNDP, 2011. Environmental Management Tools and Techniques - A Learning Material. National Capacity Self Assessment Project. Royal Government of Bhutan, Thimphu, www.nec.gov.b.

UNEP, 2019. Emissions Gap Report 2019. United Nations Environment Programme (UNEP), Nairobi.

UNEP, 2015. An Introduction to Environmental Assessment. UNEP World Conservation Monitoring Centre, 219 Huntingdon Road, Cambridge, CB3 0DL, UK.

US EPA, 2006. Life Cycle Assessment: Principles and Practice. Scientific Applications International Corporation (SAIC).

van de Kaa, G., van Ek, M., Kamp, L.M., Rezaei, J., 2020. Wind turbine technology battles: Gearbox versus direct drive - opening up the black box of technology characteristics. Technol. Forecast. Soc. Change 153, 119933. https://doi.org/10.1016/j.techfore.2020.119933

Vargas, A. V., Zenón, E., Oswald, U., Islas, J.M., Güereca, L.P., Manzini, F.L., 2015. Life cycle assessment: A case study of two wind turbines used in Mexico. Appl. Therm. Eng. 75, 1210–1216. https://doi.org/10.1016/j.applthermaleng.2014.10.056

Varun, Prakash, R., Bhat, I.K., 2010. Life cycle energy and GHG analysis of hydroelectric power development in India. Int. J. Green Energy 7, 361–375. https://doi.org/10.1080/15435075.2010.493803

Vattenfall-AB, 2013a. Environmental Product Declaration- Electricity from Vattenfall´s wind farms in the UK.

Vattenfall-AB, 2013b. Certified Environmental Product Declaration of Electricity from Vattenfall AB ' s Swedish Windpower Plants.

Vattenfall AB, 2015. Certified Environmental Product Declaration EPD ® of Electricity from Vattenfall ' s Nordic Hydropower 1–47.

Venås, C., 2015. Life cycle assessment of electric power generation by wind turbines containing rare earth magnets. Master thesis. Norwegian University of Science and Technology. Norway.

Vestas, 2015. Life Cycle Assessment of Electricity Production from an onshore V110-2 . 0MW Wind Plant, Vestas Wind Systems A/S Vestas.

Vigon, B.W., Toole, D.A., Cornaby, B.W., Latham, H.C., Harrison, C.L., Boguski, T.L., Hunt, R.G., Sellers, J.D., 1993. Life-Cycle Assesment: Inventory Guidelines and Principles. US EPA.

Vougioukli, A.Z., Didaskalou, E., Georgakellos, D., 2017. Financial Appraisal of Small Hydro-Power Considering the Cradle-to-Grave Environmental Cost: A Case from Greece Adamantia. Energies 10, 1–20. https://doi.org/10.3390/en10040430

Walmsley, T.G., Walmsley, M.R.W., Atkins, M.J., 2018. Energy Return on energy and carbon investment of wind energy farms: A case study of New Zealand. J. Clean. Prod. 167, 885–895. https://doi.org/10.1016/j.jclepro.2017.08.040

Wang, Shifeng, Wang, Sicong, 2015. Impacts of wind energy on environment: A review. Renew. Sustain. Energy Rev. 49, 437–443. https://doi.org/10.1016/j.rser.2015.04.137

Wang, Shifeng, Wang, Sicong, Smith, P., 2015a. Quantifying impacts of onshore wind farms on ecosystem services at local and global scales. Renew. Sustain. Energy Rev. 52, 1424–1428. https://doi.org/10.1016/j.rser.2015.08.019

Wang, Shifeng, Wang, Sicong, Smith, P., 2015b. Ecological impacts of wind farms on birds : Questions , hypotheses , and research needs. Renew. Sustain. Energy Rev. 44, 599–607. https://doi.org/10.1016/j.rser.2015.01.031

Wang, W., Wang, W., Ecole, O., Lyon, C. De, Lyon, L.É.C.D.E., De, E.D.E.S.S., 2011. Eco-design of power transmissions systems. Other. Ecole Centrale de Lyon, 2011. English. <NNT : 2011ECDL0022>. <tel-00627890> HAL.

Wang, Y., Sun, T., 2014. Life cycle assessment of CO 2 emissions from wind power plants : Methodology and case studies. Renew. Energy 43, 30–36. https://doi.org/10.1016/j.renene.2011.12.017

Wang, Y., Sun, T., 2012. Life cycle assessment of CO 2 emissions from wind power plants : Methodology and case studies. Renew. Energy 43, 30–36. https://doi.org/10.1016/j.renene.2011.12.017

Wanga, L., Wanga, Y., Dub, H., Zuoc, J., Lid, R.Y.M., Zhoua, Z., Bia, F., Garvlehna, M.P., 2019. A comparative life-cycle assessment of hydro-, nuclear and wind power: A China study. Appl. Energy 249, 37–45. https://doi.org/10.1016/j.apenergy.2019.04.099

WEC, 2004. Comparison of energy systems using life cycle assessment. A Special report of the World Energy Council, London W1B 5LT, UK.

Wei, W., Larrey-Lassalle, P., Faure, T., Dumoulin, N., Roux, P., Mathias, and J.-D., 2014. How to Conduct a Proper Sensitivity Analysis in Life Cycle Assessment: Taking into Account Correlations within LCI Data and Interactions within the LCA Calculation Model. Environ. Sci. Technol.

Weidema, B.P., 2015. Comparing Three Life Cycle Impact Assessment Methods from an

Endpoint Perspective. J. Ind. Ecol. 19, 20–26. https://doi.org/10.1111/jiec.12162
Weidema, B.P., Wesnaes, M.S., 1997. Data quality management for life cycle inventories-an example of using data quality indicators. J. Clean. Prod. 4, 167–174.
Weisser, D.A., 2007. A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies. Energy 32, 1543–1559. https://doi.org/10.1016/j.energy.2007.01.008
Wilkinson, W.L., 2001. Environmental impact of electricity generation. Trans. R. Soc. South Africa 56, 131–133. https://doi.org/10.1080/00359190109520511
WNA, 2011. Comparison of Lifecycle Greenhouse Gas Emissions of Various Electricity Generation Sources, World Nuclear Association.
Wolde-Ghiorgis, W., 2002. Renewable energy for rural development in Ethiopia : the case for new energy policies and institutional reform. Energy Policy 30, 1095–1105.
World Bank, 1964. Ethiopia: The Ethiopian Electric Light and Power Authority Project Eth1opia.
Wudu, M., 2015. Wind Energy Resource Analysis - A Case Study of Aysha Wind Farm. Master thesis. Center of Energy Technology Addis Ababa University, Addis Ababa. Addis Ababa University.
Xu, L., Pang, M., Zhang, L., Poganietz, W.R., Dattatraya, S., Marathe, S.D., 2018. Life cycle assessment of onshore wind power systems in China. Resour. Conserv. Recycl. 132, 361–368. https://doi.org/10.1016/j.resconrec.2017.06.014
Yan, M.J., Humphreys, J., Holden, N.M., 2013. Evaluation of process and input – output-based life-cycle assessment of Irish milk production. J. Agric. Sci. (2013), 151, 701–713. https://doi.org/10.1017/S0021859613000257
Yang, J., Chen, B., 2015. Life Cycle Assessment of Wind Power Generation System. In Handbook ofClean Energy Systems, John Wiley & Sons, Ltd., in: Handbook of Clean Energy Systems. https://doi.org/10.1002/9781118991978.hces115
Yang, J., Chen, B., 2013. Integrated evaluation of embodied energy , greenhouse gas emission and economic performance of a typical wind farm in China. Renew. Sustain. Energy Rev. 27, 559–568. https://doi.org/10.1016/j.rser.2013.07.024
Yang, X., Patterson, D., Hudgins, J., 2012. Permanent magnet generator design and control for large wind turbines. PEMWA 2012 - 2012 IEEE Power Electron. Mach. Wind Appl.

https://doi.org/10.1109/PEMWA.2012.6316367

Yang, Y., 2016. Two sides of the same coin : consequential life cycle assessment based on the attributional framework. J. Clean. Prod. 127, 274–281. https://doi.org/10.1016/j.jclepro.2016.03.089

Yoo, S.H., 2005. Electricity consumption and economic growth: Evidence from Korea. Energy Policy 33, 1627–1632. https://doi.org/10.1016/j.enpol.2004.02.002

Yuguda, T.K., Li, Y., Xiong, W., Zhang, W., 2019. Life cycle assessment of options for retrofitting an existing dam to generate hydro-electricity. Int. J. Life Cycle Assess. 25, 57–72. https://doi.org/10.1007/s11367-019-01671-1

Zamagni, A., Pesonen, H.L., Swarr, T., 2013. From LCA to Life Cycle Sustainability Assessment: Concept, practice and future directions. Int. J. Life Cycle Assess. 18, 1637–1641. https://doi.org/10.1007/s11367-013-0648-3

Zampori, L., Saouter, E., Schau, E., Cristobal, J., Castellani, V., Sala, S., 2016. Guide for interpreting life cycle assessment result, Eur 28266 En. https://doi.org/10.2788/171315

Zhang, Jing, Luo, C.Y., Curtis, Z., Deng, S.H., Wu, Y., Li, Y.W., 2015. Carbon dioxide emission accounting for small hydropower plants - A case study in Southwest China. Renew. Sustain. Energy Rev. 47, 755–761. https://doi.org/10.1016/j.rser.2015.03.027

Zhang, J., Xu, L., Cai, Y., 2018. Water-carbon nexus of hydropower: The case of a large hydropower plant in Tibet, China. Ecol. Indic. 92, 107–112. https://doi.org/10.1016/j.ecolind.2017.06.019

Zhang, Jin, Xu, L., Li, X., 2015. Review on the externalities of hydropower: A comparison between large and small hydropower projects in Tibet based on the CO2 equivalent. Renew. Sustain. Energy Rev. 50, 176–185. https://doi.org/10.1016/j.rser.2015.04.150

Zhang, Q., Karney, B., MacLean, H.L., Feng, J., 2007. Life-cycle inventory of energy use and greenhouse gas emissions for two hydropower projects in China. J. Infrastruct. Syst. 13, 271–279. https://doi.org/10.1061/(ASCE)1076-0342(2007)13

Zhang, S., Pang, B., Zhang, Z., 2015. Carbon footprint analysis of two different types of hydropower schemes: Comparing earth-rockfill dams and concrete gravity dams using hybrid life cycle assessment. J. Clean. Prod. 103, 854–862.

https://doi.org/10.1016/j.jclepro.2014.06.053

Zimmermann, P., Frischknecht, R., Menard, M., 1996. Background Inventory Data. In Life Cycle Assessment (LCA) — Quo vadis?, in: Life Cycle Assessment (LCA) — Quo Vadis? pp. 39–49.

Zimmermann, T., Rehberger, M., Göling-Reisemann, S., 2013. Material Flows Resulting from Large Scale Deployment of Wind Energy in Germany. Resources 2, 303–334. https://doi.org/10.3390/resources2030303

Annex A - LCI computation methods

In LCI analysis, there two commonly used computational methods: namely the sequential and matrix (inversion) methods. A short description of these methods with examples are given below, mainly extracted from (Heijungs and Suh, 2002; Suh and Huppes, 2005).

A.1. Sequential method

LCI compilation using a process flow diagram has been the most common practice among LCA practitioners. In process flow diagrams, unit processes of a product system are interconnected through intermediate product (or commodity) flows. The sequential method uses this relationship to calculate the LCI of product systems in three steps.

Step 1. The amount of intermediate commodities for fulfilling a certain functional unit is obtained.

Step 2. The amount of intermediates are multiplied with the amount of environmental interventions generated to produce them.

Third 3. The LCI of the product system is calculated by summing the results of step 2.

A.2. Matrix inversion method

This method applies four basic steps to compute LCI of analyzed system.

Step 1 - Formulation of technology matrix

Here, we define a **nxn** LCA technology matrix $A = [a_{ij}]$ such that an element, a_{ij} shows flows (i.e., input or output) of commodity i of unit process j for certain duration of process operation. The input and output of the given process are noted by negative and positive values respectively. We assume that processes at stake are being operated under a steady state condition, so that the rate at which inputs consumed and the rate at which output produced for each process does not alter.

	Process 1	Process 2	...	Process n
Flow 1	a_{11}	a_{12}	...	a_{1n}
Flow 2	a_{21}	a_{22}	...	a_{2n}
⋮	⋮	⋮	⋮	⋮
Flow n	a_{n1}	a_{n2}	...	a_{nn}

Step 2 - Formulation of the scaling factors

Scaling factors (also called scaling vector), dented by **s,** is used to upscale or downscale elements of unit processes to produce the required net output of the system. Then, net output (i.e., functional unit) of the system **f** is given by:

$$\mathbf{As = f} \quad \text{Eq. 1}$$

Given that the technology matrix **A** is known and **f** the final demand vector f is known, **eq.1** can be solved to yield the scaling factor **s:**

$$\mathbf{s = A^{-1}f} \quad \text{Eq. 2}$$

Step 3 - Formulation of intervention matrix

In this point we define the interventions with a **pxn** matrix $\mathbf{B = [b_{ij}]}$ of which an element shows the amount of pollutants or natural resources i emitted or consumed by the unit process during the operation time that $\mathbf{a_{ij}}$ is specified. Matrix **B** may be called the intervention matrix, because it represents the environmental interventions of unit processes. Apart from the fact that upscaling a unit process affects the economic flows, it also affects the environmental flows in the same way.

Step 4 – Computing the system LCI

The product of the intervention matrix (**B**) and the scale factor vector (**s**) produces the LCI of system under study, as shown in equation 4 below.

$$\mathbf{M} = \mathbf{Bs} \qquad \text{Eq. 3}$$

Substituting for **s** from equation 2 results in equation 5 as follows:

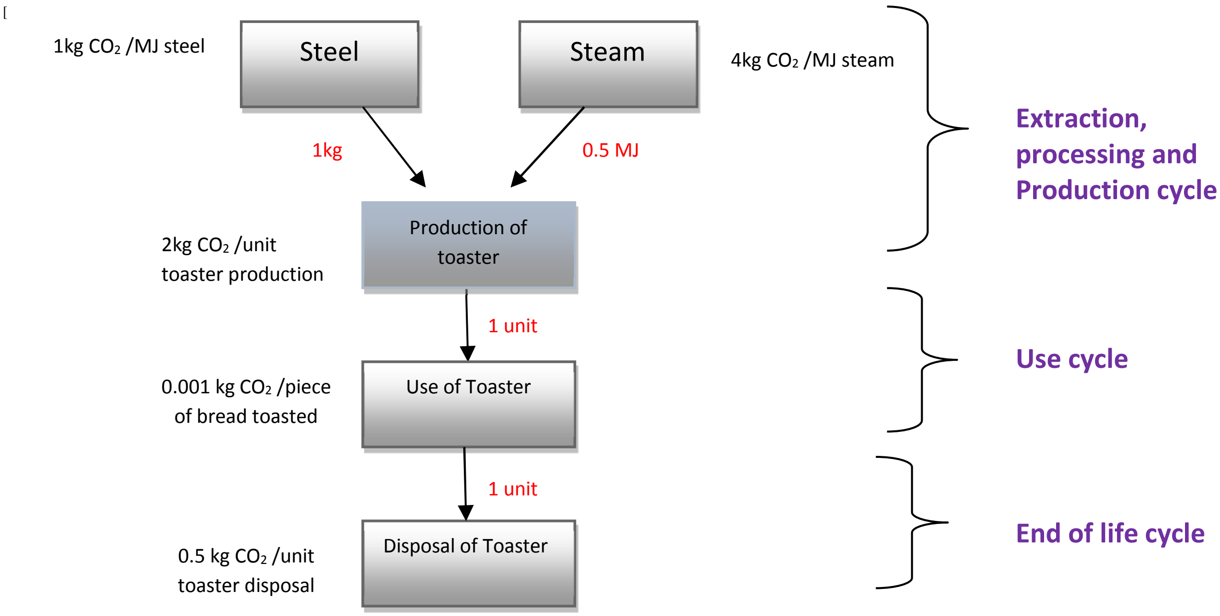
$$\mathbf{M} = \mathbf{BA}^{-1}\mathbf{f} \qquad \text{Eq. 4}$$

Where **M** is the total environmental intervention matrix (or the inventory vector) and **f** is the final demand vector that shows the functional unit of the system.

Example

Suppose a unit of toaster is produced using 1 kg of steel and 0.5 MJ of steam, and is then used for 1,000 times and disposed of. Producing 1kg of steel, 1MJ of steam and 1 unit of toaster requires 1, 4 and 2 kg of CO_2 emission, respectively. Baking 1 piece of bread using the toaster and disposal of 1 unit of toaster is assumed to emit 0.001 and 0.5kg of CO_2, respectively. Suppose that the toaster under study produces 1,000 pieces of bread during its life time, and the functional unit of this product system is given by 1,000 pieces of bread/toast. Then one can calculate the amount of commodity requirements and resulting environmental intervention as follows:

Process flow diagram:



Solutions

1. Using sequential method to calculate system LCI from process flow diagram.

$$\left(\frac{1kgCO_2}{kg\ steel} * 1kg\ steel\right) + \left(\frac{4kgCO_2}{MJ\ steam} * 0.5\ MJ\ steam\right)$$

$$+\left(\frac{2kgCO_2}{unit\ toaster\ produced} * 1unit\ toaster\ produced\right)$$

$$+\left(\frac{0.001kgCO_2}{piece\ of\ bread\ toasted} * 1000\ bread\ toasted\right)$$

$$+\left(\frac{0.5kgCO_2}{unit\ toaster\ disposed} * 1\ unit\ toaster\ disposed\right) = \mathbf{6.5kgCO_2}$$

2. Using matrix inversion method

The commodity (intermediate product) flows of the product system of the above problem can be expressed by the LCA technology matrix as well as shown in the table (array) below.

	Steel production 1	Steam production 2	Toaster production 3	Use of toaster process 4	Disposal of toaster
Kg of steel	1	0	-1	0	0
MJ of steam	0	1	-0.5	0	0
Unit of toaster	0	0	1	-1	0
Piece of bread toasted	0	0	0	1000	0
Unit of disposed toaster	0	0	0	1	-1

That means:

$$A = \begin{bmatrix} 1 & 0 & -1 & 0 & 0 \\ 0 & 1 & -0.5 & 0 & 0 \\ 0 & 0 & 01 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 \end{bmatrix} \quad \text{Eq. 6}$$

The environmental intervention matrix (i.e., unit emissions) and the commodity net output of the system are given by respectively.

$$\mathbf{B} = \begin{bmatrix} 1 & 4 & 2 & 0.001 & 0.5 \end{bmatrix} \quad \text{Eq. 7}$$

and

$$\mathbf{f} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1000 \\ 0 \end{bmatrix} \quad \text{Eq. 8}$$

The inventory result of this product system is now calculated using **eq. 5** as

$$\mathbf{M} = \mathbf{BA^{-1}f} = \begin{bmatrix} 1 & 4 & 2 & 1 & 0.5 \end{bmatrix} \begin{bmatrix} 1 & 0 & 1 & 0.001 & 0 \\ 0 & 1 & 0.5 & 0.0005 & 0 \\ 0 & 0 & 1 & 0.001 & 0 \\ 0 & 0 & 0 & 0.001 & 0 \\ 0 & 0 & 0 & 0.001 & 0 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1000 \\ 0 \end{bmatrix} = 6.5 \text{ kg } CO_2 \quad \text{Eq. 9}$$

Therefore, the two methods give result.

Annex B. LCI data of wind power system in Ethiopia per 1 kWh

Subsystems	Subassembly	Materials	Unit	Input/kWh
Wind turbines	Rotor Assembly	Cast iron	kg	1.74E-04
		Glass fiber	kg	1.64E-04
		Epoxy resin	kg	7.64E-05
		Low alloyed steel	kg	1.33E-04
		Adhesives	kg	1.59E-05
		Chromium steel	kg	1.22E-05
		GFRP	kg	5.08E-06
		Polymers	kg	8.99E-06
		Paint	kg	3.87E-06
		Blasa wood	kg	3.40E-06
		Aluminum	kg	1.69E-07
		Cables	kg	6.01E-07
		Brass	kg	2.64E-07
		Copper	kg	1.91E-08
		Electricity, medium voltage	kWh	5.20E-04
	Nacelle assembly	Low alloyed steel	kg	4.57E-04
		Chromium steel	kg	9.63E-05
		Cast iron	kg	3.02E-04
		Copper	kg	2.63E-05
		Aluminum	kg	4.86E-06
		Brass	kg	2.26E-07
		Polymers	kg	2.56E-06
		GFRP	kg	1.69E-05
		Paint	kg	1.62E-06
		Electrical/electronic component	kg	9.23E-06
		Lubricant /hydraulic oil	kg	5.96E-06
		Cables	kg	4.19E-06
		Permanent magnet	kg	8.10E-06
		Electricity, medium voltage	kWh	5.14E-03
	Tower assembly	Low alloyed steel	kg	2.11E-03
		Aluminum	kg	4.39E-06
		Electricity, medium voltage	kWh	6.42E-04
	Transportation	Transport, freight, lorry >32 metric ton	tkm	3.57E-03
		Transport, freight, lorry 16-32 metric ton	tkm	5.40E-04
		Transport, freight, lorry 7.5-16 metric ton	tkm	1.83E-04
		Transport, freight, lorry, unspecified	tkm	1.32E-04
		Transport, freight, sea, transoceanic ship	tkm	3.96E-02
	Construction	Land transformation, from agriculture	m2	3.52E-04
		Excavation	m3	1.14E-03
		Concrete	m3	5.55E-06
		Reinforcing steel	kg	3.60E-02

		low alloyed steel (foundation cap)	kg	1.58E-04
		Electricity, medium voltage	kWh	5.06E-05
Internal connection network	Unit transformer	Low alloyed steel	kg	8.13E-05
		Cast iron	kg	4.78E-07
		Aluminum	kg	3.72E-06
		GFRP	kg	2.44E-07
		Copper	kg	5.98E-06
		Brass	kg	2.16E-08
		Polyester resin	kg	5.85E-07
		Porcelain	kg	1.46E-06
		Polymer	kg	4.32E-07
		Paint	kg	2.00E-08
		Electricity	kWh	3.53E-03
		Heat, natural gas	MJ	1.50E-04
	Cable	Low alloyed steel	kg	1.62E-09
		Copper	kg	1.26E-06
		PVC	kg	1.94E-07
		XLPE	kg	1.39E-09
	Grounding system	Copper	kg	9.05E-06
		Aluminum	kg	4.62E-05
		XLPE	kg	4.56E-06
	Transportation	Transport, freight, lorry, unspecified	tkm	1.23E-03
		Transport, freight, sea, transoceanic ship	tkm	6.12E-03
	Construction	Land requirement	m2	4.91E-07
		Excavation, hydraulic digger	m3	6.56E-07
		Concrete	m3	8.42E-08
		Reinforcing steel	kg	9.46E-06
MV subsystem	Collection switchgears	Low alloyed steel	kg	6.74E-07
		Copper	kg	1.55E-07
		XLPE	kg	2.17E-08
		Electronics, for control units	kg	4.95E-10
		Aluminum	kg	8.47E-09
		Brass	kg	5.20E-10
		GFRP	kg	6.45E-09
		Epoxy resin	kg	4.83E-10
	Earthing system	Low alloyed steel	kg	2.19E-05
	OH conductors	Low alloyed steel	kg	7.24E-06
		Aluminum, cast alloy	kg	1.60E-05
	Power cables	Steel, low-alloyed	kg	7.83E-08
		Copper	kg	5.18E-06
		PVC	kg	9.73E-09
		XLPE	kg	2.82E-09
	Steel poles & gantry	Low alloyed steel	kg	9.62E-05
		Transport, freight, lorry, unspecified	tkm	2.88E-04

	Transportation	Transport, freight, sea, transoceanic ship	tkm	1.01E-03
	Construction	Land requirement	m2	1.08E-05
		Excavation	m3	1.18E-05
		Concrete	m3	7.19E-07
		Reinforcing steel	kg	9.80E-05
HV subsystem	Power transformer	Low alloyed steel	kg	2.20E-05
		Copper	kg	4.84E-06
		Porcelain	kg	4.01E-07
		Kraft paper	kg	1.44E-06
		Aluminum	kg	6.52E-07
		GFRP	kg	4.91E-08
		Epoxy resin	kg	5.67E-08
		Glass fiber	kg	1.16E-07
		Electricity, medium voltage	kWh	9.04E-04
	Civil structures	Low alloyed steel	kg	5.46E-06
	Switchgear devices	Low alloyed steel	kg	4.22E-06
		Copper	kg	3.77E-07
		Porcelain	kg	7.83E-06
		Aluminum	kg	1.30E-06
		Kraft paper	kg	2.83E-07
		Epoxy resin	kg	3.30E-08
		Chromium steel	kg	6.31E-08
		Zinc oxide	kg	1.93E-08
		Zinc	kg	2.74E-08
		Sulfur hexafluoride	kg	3.08E-08
		Brass	kg	1.72E-08
		XLPE	kg	3.07E-08
	OH conductors	Low alloyed steel	kg	9.92E-07
		Aluminum	kg	2.65E-06
		Zinc	kg	7.98E-08
	Earthing system	Low alloyed steel	kg	2.39E-06
	Transmission towers	Low alloyed steel	kg	2.69E-05
	Grid connection	Low alloyed steel	kg	5.71E-07
		Copper	kg	4.76E-08
		Porcelain	kg	1.03E-06
		Aluminum	kg	1.86E-07
		Kraft paper	kg	6.15E-08
		Epoxy resin	kg	6.22E-09
		Zinc oxide	kg	4.24E-09
		Zinc	kg	2.87E-09
		Sulfur hexafluoride	kg	4.67E-09
		XLPE	kg	4.14E-09
	Transportation	Transport, freight, lorry >32 metric ton	tkm	3.58E-05
		Transport, freight, lorry, unspecified	tkm	9.00E-05

		Transport, freight, sea, transoceanic ship	tkm	9.44E-04
	Construction	Land requirement	m2	4.62E-06
		Excavation	m3	8.82E-06
		Concrete	m3	2.10E-07
		Reinforcing steel	kg	1.11E-04
		Sand	kg	5.19E-06
Replaceable parts (Operation and maintenance)	Materials for replacement	Low alloyed steel	kg	6.58E-05
		Chromium steel	kg	1.86E-05
		Cast iron	kg	4.88E-05
		Copper	kg	3.07E-06
		Aluminum	kg	4.46E-07
		Brass	kg	7.01E-09
		Polymers	kg	3.97E-06
		Glass fiber	kg	8.15E-05
		GFRP	kg	2.25E-07
		Polyester resin	kg	3.80E-05
		Paint	kg	2.34E-06
		Electronics	kg	7.25E-07
		Blasa wood	kg	1.70E-06
		Adhesives	kg	7.91E-06
		Cables	kg	2.79E-07
		Permanent magnet	kg	5.36E-07
	Operation	Mineral oil (20 years consumption)	kg	6.57E-05
		Mineral oil (15 years consumption)	kg	9.60E-05
		Mineral oil (25 years consumption)	kg	9.22E-04
	Transportation	Transport, freight, lorry, unspecified	tkm	2.93E-04
		Transport, freight, sea, transoceanic ship	tkm	1.47E-03

NB: HV= high voltage; MV electricity= medium voltage electricity; GFRP = glass fiber reinforced plastic