Life cycle sustainability assessment of infrastructure projects: An application in energy production

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This is to certify that the

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This thesis is dedicated to my parents and my respected teachers!

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ABSTRACT

Infrastructure projects pose serious challenges and opportunities in the development of a country. A better road infrastructure will ensure that country's economic wheel keeps running and a better electricity infrastructure would keep the national bulb lighting. Without taking a life cycle perspective of such development projects, it is very hard to reach to a mutual decision. Sustainable development of infrastructure needs consideration on all three dimensions of sustainability. Pakistan is facing problems in the area of power production infrastructure due to various causes and power outage has become a soaring issue due to a tenacious and spreading gap between demand and supply. Moreover, the current production is causing severe environmental and energy security issues due to reliance on thermal sources. Stakeholders are showing great concern to address these issues but a significant knowledge gap results into discrepancies in policies that govern energy sector. A comprehensive approach over the sustainability is missing due to non-adoption of life cycle thinking. This study present a new line of thinking by delivering an integrated life cycle sustainability assessment of the electricity sector in Pakistan. In total, 20 sustainability indicators have been assessed covering life cycle of seven power production sources currently in use. These sources have been ranked using weighted multi-criteria decision analysis. Hydropower energy is found as the most sustainable option having lowest environmental and economic impacts. While due to worst economic and social impacts, generation with fuel oil is found to be least sustainable. Establishing tradeoffs between different electricity options, this study presents an unbiased view emphasizing the use of life cycle approach in sustainability assessment for improving energy policies.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

SD	Sustainable Development
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
S-LCA	Social Life Cycle Assessment
OECD	Organization for Economic Co-operation and Development
TBL	Triple Bottom Line
LCSA	Life Cycle Sustainability Assessment
TOE	Ton Oil Equivalent
GWh	Gaga Watt Hour
MW	Mega Watt
KWh	Kilo Watt Hour
SDGs	Sustainable Development Goals
GWP	Global Warming Potential
O&M	Operational and Maintenance
NEPRA	National Electric Power Regulatory Authority
WAPDA	Water and Power Development Authority
PPIB	Private Power & Infrastructure Board
DCB	Dichlorobenzene
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
CML	Institute of Environmental Sciences, Leiden University
UNEP	United Nations Environment Programme
SETAC	Society of Environmental Toxicology and Chemistry
ISO	International Organization for Standardization

Chapter 1

INTRODUCTION

1.1 Preface

Sustainability has appeared as one of the top most considerations of modern age and is strongly considered as essential concept to guide global development. Achieving sustainability goals has posed important challenges to the scientific community in providing efficient and reliable tools and techniques (Kates et al., 2005; Van den Berg et al., 2007). It covers various sectors and industries including manufacturing, infrastructure, construction, urban development, agriculture, mining/mineral extraction, educational campuses or institutes, etc. (Aboushady and El-Sawy, 2013; Cole and Wright, 2003).

Sustainable development (SD) is a dynamic process aimed at balancing the competing needs, and has evolved from environmental and economic domains to embrace the societal, technological, institutional and political necessities of the world (Azapagic et al., 2004b; Meyar-Naimi and Vaez-Zadeh, 2013; Štreimikienė et al., 2016). Because of the growing concerns over unsustainable practices, necessary processes and methods have been developed and used to assess, manage and improve SD. Since SD has an overarching mandate, one of the widely adopted approaches for achieving it is life cycle thinking which enhances the sustainability in different sectors and industries (Ness et al., 2007).

1.1.1 Life cycle sustainability analysis (LCSA)

Sustainability is understood differently by different stakeholders due to their interests, participation, role and understanding (Kates et al., 2001). Therefore, the assessment of sustainability has its own challenges and boundaries (Perdan and Azapagic, 2011). In the past decades, different methods and tools have emerged to assess and improve sustainable development. These approaches can be categorized based on numerous factors and aspects (Ness et al., 2007; Singh et al., 2009).

Life cycle thinking as a sustainability assessment approach was firstly adopted to solve environmental issues. Since human activities are linked with complex web of environmental outcomes which cannot be explicitly associated with a single stage of product life (Menoufi, 2011). And there was a requirement to introduce a systematic and comprehensive approach that focuses on whole life of a product and goes beyond single issue and direct impact. Thus, life cycle assessment (LCA) was introduced to elaborate a full picture of human interactions with the environment and avoid shifting of environmental impacts from one life cycle stage to another (Azapagic et al., 2004a). Life cycle costing (LCC) and social life cycle assessment (S-LCA) are adopted in parallel to LCA to cover economic and social aspects of product life respectively (UNEP, 2012).

Based on the Triple Bottom Line (TBL) thinking of sustainability and as an integrated tool, life cycle sustainability assessment (LCSA) gives broadened picture of LCA and LCC to cover the three pillars of sustainability (Guinée, 2016; Heijungs et al., 2010; Klöpffer and Renner, 2008). LCSA is an effective tool to attain sustainable consumption and production and provides guidance to enterprises and people in policy making regarding sustainable development (Heijungs et al., 2010; UNEP, 2012). LCSA improves the decision making by providing more reliable calculations of the sustainability results in the life cycle perspective to take decisions on technology systems. By providing a clear picture of negative and positive impacts along the product life cycle, it helps in trade-offs between the three dimensions of sustainability, products and generations, and life cycle stages and impacts (UNEP, 2012).

1.1.2 Sustainability on energy production

Power or electricity is a vital part of routine life and its effective supply is essential for existing and emerging technologies. Its generation should be increased by using advancement in techniques keeping in view the social and economic impacts (Jones, 1985). Availability of cheap, reliable and clean energy supply to domestic, industrial and commercial divisions of the country is critical to its sustainable growth (Qudrat-Ullah, 2015). Further, Energy production affects various environmental, economic and social issues and has major significance for SD of a country. A sustainable mean of energy production can improve economy, quality of life and social wellbeing of a country (Maxim, 2014). Starting with the environmental issues, energy production has also been studied to enhance economic, social and technological aspects in the developed as well as developing regions. Research on sustainable energy production varies with respect to many features such as depth of study, technological level, temporal and geographical distribution, and tools used for assessment and integration of different sustainability dimensions (Santoyo-Castelazo and Azapagic, 2014).

1.1.3 Energy production and Pakistan

The primary sources of energy production in Pakistan consists of oil, gas, hydro, coal, nuclear and wind. Energy supplies of the country during 2013-14 increased by 3.5% and reached 66.85 MTOE (metric ton oil equivalent) as compared to 64.59 MTOE during the same period last year and during 2014-15, the total energy generated in the country was 109,059 GWh (NEPRA, 2015).

Since energy generation is one of the most important factors to cultivate the economy and improve living standards of a country, a safe and robust energy supply to cater for the soaring demands of developing infrastructure and industry is essential (Kessides, 2013). Pakistan is a developing country and its electricity consumption is growing annually at a rate of 11% (Awan and Rashid, 2012). Since the last decade, it is facing serious outages and has critically failed to keep a balance between supply and demand. Resultantly, shortage of electricity has become one of the key governance issues along with the challenges of political disorder, terrorism, low literacy, unemployment, lower GDP and frequent change in government policies (Lodhi and Malik, 2013; Sakrani et al., 2012). In 2015, the total installed capacity of the country was 24,823 MW while maximum demand was 26,437 MW (NEPRA, 2015). Owing to this gap, authorities having been taking great initiatives to find panacea in the form of energy summits and long debates over ways to address electricity shortages. Various possible renewable and non-renewable sources of energy production are being considered to propose short-, mid- and long-term solutions to this nuisance (Valasai et al., 2017). However, the continuum in energy crisis has put question on legitimacy and credibility of system and policy makers.

Further, a large share of almost two-thirds (69,988 GWh) of the entire generation is from thermal sources which imposes to high environmental impact due to emissions. Alarmingly, the CO_2 emissions from electricity and heat production sector in Pakistan in 2013 was 31.3% of total fuel combustion (WB, 2016). Thermal generation also escalates the electricity cost due to the use of fossil fuel, bringing the issue of security of energy supply (Atilgan and Azapagic, 2016). Though in Pakistan environment has not been traditionally focused as a top priority, recent initiatives and policies show high concerns about environmental protection. Implementation of Energy Efficient Renovation (EER) and modernization aims at reducing the GHG emission along with improving efficiency and optimizing the fuel consumption for power plants (Abbasi et al., 2014). Inclusion of 'affordable and clean energy' and 'climate action' in the agenda of sustainable development goals (SDGs) 2015-2030 also highlights the ambition and desire of authorities regarding environmental protection and quality of life for the people of Pakistan (LEAD, 2016). Further, being part of Kyoto Protocol, there is high pressure for reduction of emissions related to thermal power which contributes major part of the national electricity mix (Iqbal et al., 2010). The higher reliance on fossil fuels also brings the issue of energy security as Pakistan imports 71% of total required crude oil for thermal power plants (MPNS, 2016; PBS, 2016). Other breaches that add to the ill functioning of current policy include non-adoption of life cycle thinking and knowledge gap on long-term or sustainable development in energy production (Qudrat-Ullah, 2015). Summarizing the debate, discrepancies in policies that needed to be addressed are (i) environment friendliness, (ii) stability in electricity rates for long-period, (iii) balanced closure to the gap between demand and supply, and (iv) adoption of life cycle approach. (Ford, 1983; Kessides, 2013; Qudrat-Ullah, 2015; World-Bank, 2016). In the light of this preamble, Pakistan's energy policy requires an integrated, systematic and economic approach which can help to shape a sustainable policy inception. It should represent adequate trade-off between regulatory, energic, economic and environmental aspects.

1.2 Problem statement

There is a lack of sustainable life cycle view on new projects and investment aimed at energy production which results into a short-term solution of problems. The long-term implications of such infrastructure projects need detailed investigation and analysis with the purpose of trade-off their costs with enough benefits.

1.3 Objectives

The objectives of this study are:

- To find sustainability issues and related economic, environmental and social, indicators for different energy production techniques.
- To perform life cycle sustainability assessment (LCSA) of energy production sources currently operational in Pakistan.
- To find sustainability score for each selected option to established most sustainable energy production source in country performing multi-criteria decision analysis.

1.4 Reasons for selection of the topic and relevance to national needs

Infrastructure development should be done considering the regional quality of life, economic competitiveness and enhancement in the natural environment (Fischer and Amekudzi, 2011). In modern age sustainability, has become a key issue in construction. Energy production is crucial to industry, infrastructure development, information technology, agriculture, domestic industry and more (GOP, 2015). Any nation that desires to cultivate its economy and improve living standards must have a safe and robust energy supply (Kessides, 2013). Thus, energy production should have strong concerns with improving the social, economic and environmental indicators of sustainability. From last decade Pakistan is facing serious failure in keeping the balance between energy supply and demand (Awan and Rashid, 2012; Sakrani et al., 2012). The one reason of this is absent life cycle approach and lack of long-term or sustainable development in energy production (Qudrat-Ullah, 2015). There is a strong need to bring the life cycle sustainability concept in current researches and policies to find a long-lasting solution to current energy shortfall.

Chapter 2

LITERATURE REVIEW

2.1 Sustainability development

SD has become a valuable consideration for global world and not only many international organizations like UN and EU but also a lot of councils, business entities and political parties take SD as their policy guidance and fundamental impression (Heijungs et al., 2010). SD has been given a standard definition by the Brundtland Commission (World Commission on Environment and Development) to fulfil the needs of existing generation without compromising on the capacity of coming generations to meet their needs (WCED, 1987).

SD has been studied related to various sectors and industries. Fernández-Sánchez and Rodríguez-López (2010) studied the assessment of sustainability indicators for infrastructure projects in Spain. An assessment framework is proposed by Li et al. (2012) to measure quantitative sustainability performance of manufacturing industry. Munier (2011)'s research helps in setting and measuring the sustainable urban development. In the field of agriculture sustainability, Xing et al. (2009) proposed a framework based on SD indicators. Azapagic (2004)'s study focuses to assess and improve sustainable development in mining and mineral sectors.

SD also focusses on education and numbers of declarations on sustainable campuses or institutes have been presented in past years (Wright, 2002). An assessment framework for campus sustainability (CSAF) has been developed for a university campus in Canada elaborating basic definition of sustainable campus as to protect and enhance health and wellbeing of ecosystems and humans, and addressing pertinent issues of ecosystem (water, materials, air and energy) and humans (health, governance economy social life and wealth) (Cole and Wright, 2003).

2.1.1 Sustainability assessment

Number of initiatives has been developed to assess, manage and improve SD. For example the World Business Council for Sustainable Development (WBCSD, 1997), the Global Reporting Initiative (GRI, 2004) and development of standards (OECD, 2002).

Sustainability assessment is defined by many authors and experts. As per Devuyst et al. (2001), sustainability assessment is a technique to help decision makers and stakeholders to take actions that will improve SD. Kates et al. (2001) state that the purpose of sustainability assessment is to assist decision makers to determine which actions should or should not be taken aiming to make society sustainable and to evaluate an integrated global to local societal system in short and long terms.

Different tools, techniques and frameworks have been proposed by different researchers to assess and improve SD (Singh et al., 2009). Ness et al. (2007) divided these tools and methods into three categories namely: 1. indicators and indices (further categorized into integrated and non-integrated); 2. product-related assessment tools and 3. integrated assessment tools. In study of an overview of various sustainability methodologies, Singh et al. (2009) have collected number of sustainability indices. Formulation strategy, weighting and aggregation methodology, normalization, and scaling of these indices have also been proposed.

GRI and the Institution of Chemical Engineers (IChemE) focus on three dimensions of sustainability: economic, environment and social. To measure the performance of government toward sustainable development, the UN Commission on Sustainable Development (CSD) criteria comprises of four indicators as social, environment, economic and institutional (Labuschagne et al., 2005). Keeping in view the noteworthy impacts of constructions projects on SD, different management approaches and processes have been developed to help construction community for better sustainability performance. Seven rules presented by Kibert (1994) for sustainable construction include conservation, reusing and recycling of resources, defending the natural environment, not using toxic materials, economic benefits and providing quality products. Four features of sustainable construction adopted by Hill and Bowen (1997) are social, economic, biophysical and technical aspects..

Generally, three most stressed sustainability dimensions are: 1. *environmental;* to avoid destructive and irreversible effects on the environment by effective and careful use of natural resources and with promoting use of renewable resources plus protecting and enhancing three dimensions of climate namely the soil, water and air; 2. *social;* to meet the needs of society comprising consumers, neighbours, community, employees and other project stakeholders and 3. *economic;* to grow profitability with efficient use of resources (human, materials and financial) and by competent design and better management, planning and control as shown in Figure 2.1 (Abidin and Pasquire, 2007; Hussin et al., 2013). Sustainability assessment of a project, policy or a product should cover these dimensions of sustainability. Another popular interpretation of these SD dimensions is PPP or P3 notion which refers to people (social pillar), planet (environmental pillar) and profit (economic pillar) (Heijungs et al., 2010). The term 'profit' is further modified to 'prosperity' by Summit (2002) elaborating that the economy is more than company profit.

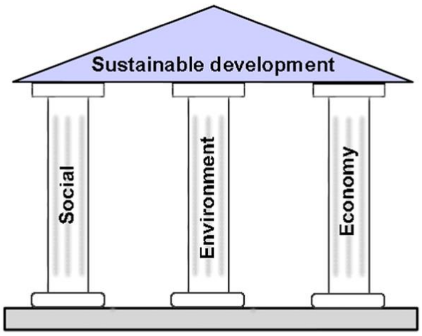


Figure 2.1 A popular way of representing SD

2.2 Life cycle thinking

As already stated SD has become as principal goal of nations. Achieving this, efforts has been put by scientific communities and researchers and one of such effort results in adoption of life cycle thinking. Which has appeared one of the widely adopted approaches to assess, manage and improve the sustainability in different sectors and industries (Ness et al., 2007). Life cycle thinking got highlighted because of increase in awareness of environmental issues and trends. (Azapagic, 2002). To the context since not only the manufacturing but other life stages such as extraction, use, re-use or re-cycling and disposal stages of most products have great impacts on environmental sustainability. So, to get strong surety in protection of environment, there is need to focus on whole life cycle of a product or activity. As a result, a systematic approach that gives a full picture without mixing of one stage with another is recognized as life cycle thinking or life cycle analysis. In other words life cycle thinking is 'cradle to grave' tactic as it covers a product from extraction of raw resources (cradle) to its disposal (grave) (EEA, 1998; Hunt et al., 1992).

2.2.1 Life cycle assessment (LCA)

Life cycle assessment (LCA) is a management tool that helps in quantification of sustainable consumption of product in its whole life in environmental perspective. LCA is used to examine actual and substantial impact on environment for the whole life cycle of a product that is during raw material procurement, production, usage and final disposal stages (Lindfors, 1995).

In 1970s it was used in some industrial sectors for energy analysis to a comprehensive environmental burden analysis. Wider consideration and methodological growth of LCA occurred in beginning of 1990s. And it appeared as an environmental management tool in corporate decision and policy making all over the world including EU, the USA, Japan, Canada, Australia and recently in India and China (Azapagic, 1999; Guinee et al., 2010).

Now a day, LCA as well-established system is used with various applications in industry, research and public policy. These applications include: design, identification, measurement, process optimization and improvement of environmental sustainable options (Azapagic, 2010).

LCA outcomes give information for making decisions related to product development, product eco-design for enhancement in production system and product choice at user level (Ness et al., 2007). LCA is also used to perform relative study between different products and services to evaluate substantial improvement through scenario changes by assessing the environmental impacts of products (Niekamp et al., 2015).

Increasing acceptance of LCA results in more creative use as well as its methodology advancement. LCA studies and applications now can be found in waste ignition, construction materials, military systems, tourism, biodiversity and noise impact. With expansion to economic and social aspects we also observe a more sophisticated LCA guidelines comprising the knowledge of active emissions, impact categorizations and dynamic, decentralized models that include economic devices, ecosystem renovation and more (Guinee et al., 2010).

After the improvement and development of decades the methodology or procedure of LCA is no widely accepted and is standardized by the International Organization for Standardization (ISO) which defines LCA as a tool to compile and evaluate environmental inputs, outputs and impacts of a product in its whole life comprising the extraction and processing of raw resources, manufacturing of product, its use and maintenance, recycling, disposal of wastages, transportation and distributions (ISO, 2006a)

As cited by Finnveden et al. (2009) and UNEP (2012) according to ISO, LCA methodology comprises of four steps as shown in Figure 2.2. As an iterative approach, phases of LCA methodology are revisited/retreated with the updating of information (Azapagic, 2010). An overview these phases is as follow.

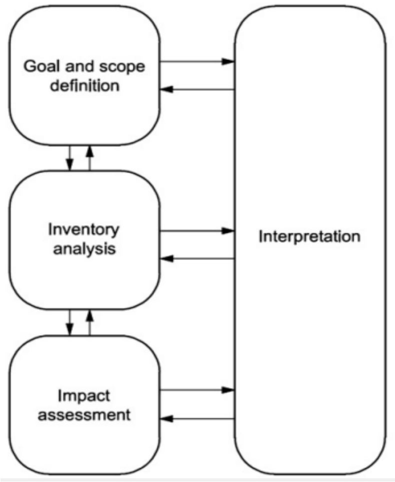


Figure 2.2 LCA methodological framework as defined by ISO

2.2.1.1 Goal and scope definition

In this phase, the purpose and intended use of study are stated with defining the system and system boundaries of study. (UNEP, 2012).

As per Azapagic (2010) outcomes of result is strongly determined by goal and scope of study. One to the most adopted system boundary is cradle to grave. Other multiple scopes includes cradle to cradle, cradle to grave and cradle to gate (Filimonau, 2016).

Functional unit as a most important part of goal and scope defining phase of LCA gives quantifications of outputs of system analysed. Different systems can be compared based on this functional unit (Jönsson, 2000; Mithraratne et al., 2007). For example, sustainability impacts of different systems (oil, natural gas and hydro techniques) of energy production can be compared based on functional unit *generation of 1 kWh of electricity production by each plant category*. Lastly this phase includes assessing the data quality and defining the data quality objectives. With availability of more information the goal and scope are revisited due to iterative nature of (Atilgan and Azapagic, 2016; UNEP, 2012).

2.2.1.2 Inventory analysis

Environmental burdens that occur during life cycle of an activity are identified and quantified in inventory stage of LCA. The burdens refer the input and outputs of system. Inputs are materials and energy used by the system and outputs represent wastes (solid, liquid and gaseous) that a system discharges out of its boundaries or environment. Life cycle inventory (LCI) includes: complete definition of the system; collection of data and its validation; environmental burdens allocation and; estimation of allocated burdens across system (Azapagic, 2010).

Researchers claim that among all stages of LCA, LCI can be highly complicated, time taking and costly due to involvement of detailed tracking of all the in- and out-flows of studied system and may include lots of individual unit processes and tracked substances (Islam et al., 2016; Trusty and Horst, 2002). The precision and level of LCI is dependent on selected inventory analysis method (Treloar, 1997).

Three main LCI methods are presently available: 1. process based modelling, 2. input output (IO) LCI and 3. hybrid method. These techniques of LCI offer different advantages and limitations and selection of one particular method is based on require accuracy level and boundary completeness (Lenzen and Crawford, 2009).

2.2.1.3 Life cycle impact assessment (LCIA)

LCIA administers data obtained from inventory analysis. In this phase, the environmental burdens are interpreted for potential environmental impacts. This interpretation is done with different methods. These methods are based on sound scientific background of environmental mechanism which relies upon specific release or emission (Menoufi, 2011). Inventory data of materials and energies, uses (inputs) and emissions (outputs) of a process/product are transformed into comprehensive environmental impact indicators (Azapagic, 2010). ISO standards provide a series of steps to yield these indicators such as classification, characterization, normalization and weighting (ISO, 2000a; ISO, 2006a).

In classification, different categories of environmental impacts are formed. These categories are based on impacts of emission and consumption of natural resources during life cycle of product/process (Menoufi, 2011).

Characterization is basically quantification of environmental impacts using a suitable LCIA method. A specific LCIA method is a collection of different characterization models where each model addresses its separate impact category. With the help of characterization model, potential contribution from each inventory emission to the environment is quantified. (Hauschild et al., 2013).

Normalization as an optional step of LCIA, broadens the context of characterization results and eases the comparison of impact indicators. The normalization factor usually signifies potential of specific geographic area and a certain timespan on impact category. Lastly, in weighting, subjective evaluations of social, political and ethical factors are incorporated into normalization indicators (ISO, 2000a; Menoufi, 2011).

Different LCIA methodologies facilitate trade-off among different product alternatives and ease the process for LCA practitioners by allowing benchmarking. These methodologies differ with respect to modelling approach (midpoint and endpoint concept), number of impact indicators, number of substances, regional validity or spatial differentiation and temporal validity of data (Pant et al., 2010). In general there are two main groups of LCIA methods: midpoint and endpoint (Azapagic, 2010). Menoufi (2011) grouped LCIA methods in four categories as follow.

1. Problem oriented or midpoint approaches: These assessment methods give quantitative modelling of impact categories up to midway of cause-effect chain. At this point, namely ‘midpoint’, LCIA impact category represents primary environmental changes

in natural environmental aspects and contributes to different environmental issues such as global warming or stratospheric ozone depletion. This approach is also acknowledged as ‘problem-oriented’ approach. Examples are CML and EDIP methods (Jolliet et al., 2004).

2. Damage oriented methods or endpoint approaches: These assessment methodologies perform environmental impact modelling all the way along cause-effect chain up to the endpoint. After the primary environmental changes in cause-effect chain, mostly biological changes occur that result in damages to area of protection (ecosystems, human health and resources). For example, stratospheric ozone depletion (midpoint indicator) can cause increase in skin cancer and can damage human health (endpoint indicator). That is why another name of ‘endpoint’ approach is ‘damage-oriented’ approach. Examples are Eco-indicator 99 and EPS methods (Bare et al., 2000).
3. The combination of these two approaches leads to third kind of impact assessment methodology that utilizes the advantages of both approaches. Examples of this kind of methods are RECIPE, Impact 2002+ and the Japanese methodology LIME (Heijungs et al., 2003; Jolliet et al., 2004) .
4. Other types of specific LCIA methodologies for assessment of specific environmental areas or certain impact categories that are not related to midpoint-endpoint modelling approach include Cumulative Energy Demand, Cumulative Exergy Demand, Ecological foot print, etc. (Menoufi, 2011).

2.2.1.4 Interpretation

Interpretation involves explaining the impact assessment result and establishing the conclusions with the purpose to guide the decision-making process. The critical environmental problems are highlighted and the importance of relative influence of specific product component or process to the environmental burden is projected (ISO, 2006b; UNEP, 2012). In other words, interpretation includes identification of main burdens and impacts, ‘hot spots’ in the life cycle assessment, sensitivity analysis, results and evaluation of LCA findings, and final recommendations (Azapagic, 2010). Further in interpretation, authentication level of results can be stated and checked by exploring the data regarding three checks: completeness, sensitivity and consistency (EEA, 1998; ISO, 2000b; Pant et al., 2010).

2.2.2 Life cycle costing (LCC)

LCC predates LCA and the life cycle thinking was firstly applied as LCC. The applications of LCC were found in 1930s when General Accounting Office (GAO) in USA requested an assessment of the costs of tractors incorporating operating and maintenance cost (Menna et al., 2016; UNEP, 2012). In 1970s, US department of Defense (DoD) established several directives for the computation of life cycle costs. LCC has been regulated for the acquisitions of military equipment and public buildings in US. In mid-1970s, LCC also gained attraction in public sector of EU. Recently, a study was commissioned by EU on the potential contribution of LCC in the sustainable construction sector (Epstein, 1996; Hunkeler et al., 2008; Langdon, 2007).

2.2.2.1 Three norms of LCC

Hunkeler et al. (2008) summarized three popular ways to define LCC (C-LCC, E-LCC and S-LCC), with respect to different features such as product system, system boundaries, number of cost borne actors, reference unit, cost categories and cost model. These three norms of LCC are further explained as following

Initially, C-LCC method was established by Blanchard (1978) and further refinements in methodology can be found in Blanchard and Fabrycky (1998), AS/NZS-4536 (1999), ISO (2001) and IEC-60300 (2004). In this method, mainly purchasing or capital price is considered and other costs are calculated by discounting costs over life period. Generally, a standard definition given by ISO is as a technique or tool to evaluate the product or service for its whole life cycle with completion of accepted performance (ISO, 2008). C-LCC includes all real and internal costs in perspective of only one market actor mainly the manufacturer or the consumer and ignores end of life costs borne by other actors (Hunkeler et al., 2008). In other words, C-LCC mainly focuses on the service or investment life span of the product and potentially ignore the upstream and downstream segments (Hunkeler et al., 2008; Menna et al., 2016).

Since C-LCC is normally used when environmental aspects are not in focus. Society of Environmental Toxicology and Chemistry (SETAC) commissioned a specific scientific working group to couple LCA with socio-economic impact assessments. With the efforts running from 2002 to 2007, this team elaborated a new approach compatible with LCA, the Environmental Life Cycle Costing (E-LCC) (Swarr et al., 2011). E-LCC was developed in order to be consistent with the system boundaries of LCA and should assess costs occurred during all of the phases of the system (Consonni et al., 2005; Menna et al., 2016). E-LCC assess all costs that are directly covered by any one or more of the actors in the product life cycle (e.g., supplier, manufacturer, user or consumer, or end of life actor) (Rebitzer and Hunkeler, 2003). It also includes the externalities that are probably internalized in the decision-relevant future, for example CO_2 taxes, and all relevant subsidies and taxes (Hunkeler et al., 2008).

The SETAC team also furnished a draft description and some methodological background for the societal life cycle costing (S-LCC) (Hunkeler et al., 2008). Having a broader perspective, it embraces all costs covered by any one actor in society, whether today or in the long-term. Further, it incorporates additional social costs and environmental externalities. In other words, it internalizes environmental and social impacts by assigning monetary values to the corresponding effects. Thus, it also characterizes socio-economic or welfare-economic assessment (Martinez-Sanchez et al., 2015; Menna et al., 2016).

2.2.2.2 LCC and ISO methodology

Despite, LCC has been used for a long time by both decision-makers and businesses, and there are numerous examples and definitions of its applications, there is still no standard or general framework for LCC. It has mainly been utilized as sector- or product-specific application (Menna et al., 2016; Reich, 2005; Sherif and Kolarik, 1981). However, a code of practice for environmental life cycle costing (LCC) has been published by SETAC. It aimed to provide readers with a solid understanding of how to apply LCC in parallel with LCA (Swarr et al., 2011) and provides guidance that builds on the four-phase structure of ISO 14040 standard. It eases application of consistent system boundaries and balances implications of LCC and LCA for a given product system. As per this code of practice goal and scope definition is alike to that of an LCA. However, key considerations are as follow.

- Both LCA and LCC studies should refer to a consistent definition of the product system and cut off criteria do not conflict with the intended goal and scope of the study.
- Selection of an appropriated discount rate
- Data should be presented in a way to fairly exhibit the viewpoints of all life cycle actor (whether supplier, manufacturer or consumer) and avoid their potentially conflicting perspectives of costs.
- To facilitate the consistent collection of data, cost breakdown structure (CBS) should be developed.
- Double counting of the same environmental impacts should be avoided in both financial and physical terms.

The inventory is performed much like that of LCA and therefore economic life cycle inventory faces almost similar data access and quality issues faced in LCA. Procedurally, inventoried cost is aggregated by cost categories. This helps to better understand the costing systems in supply chain for studied countries or regions (Ciroth, 2009; UNEP, 2012). There is no need for comparative impact assessment phase in LCC, because all data is inventoried in a single unit of measure, namely currency. As aggregate cost data displays a direct measure of financial impact, no characterization or weighting of inventory data is needed in LCC. Lastly, interpretation is done in a similar fashion as that of LCA (Swarr et al., 2011).

2.2.3 Social life cycle assessment (S-LCA)

S-LCA considers the social impact of products in their lifespan from extraction of raw materials to final disposal. It assesses the social and socio-economic aspects of products and evaluates the potential positive and negative impacts associated to these aspects (UNEP, 2009). Social welfare is considered as one of the foremost development goals for any society. A key aim of public policies is to improve social and economic benefits while minimizing their impacts. Establishing the judgement of social impacts and benefit is very tough and debated because the perception of social issue largely depends on cultural norms, different ethics, and lifestyles of the societies (Sala et al., 2015). Discussions on social aspect of sustainability throughout product life cycle started in the 1980s. Initially, O'Brien et al. (1996) gave the idea of complementing S-LCA with LCA. Klöpffer (2003) and Weidema (2006) further enlarged the discussion on the integration or alignment of S-LCA with LCA methodology.

2.2.3.1 Methodological development of S-LCA

S-LCA integrates traditional LCA methodology while focusing on social impacts and its definition has been established in complementary to environmental LCA for the assessment of the social sustainability of a product (Finkbeiner et al., 2010). However, in contrast to LCA, the level of methodological development, application, and harmonization of S-LCA is still at initial stage (Sala et al., 2015).

Acknowledging the requirement for the integration of social measures into LCA, the United Nations Environment Programme (UNEP) and SETAC collaboration published the guidelines for S-LCA of products (UNEP, 2009). These guidelines suggested to assess social impacts related to three area of protections (AoP); human health, ecotoxicity and resource depletions. The five main stakeholder categories suggested by guidelines are worker, local community, society, consumer and value chain actor that are directly or indirectly affected by the social impacts. Number of subcategories are defined under each stakeholder, including for example child labour, fair salary, health and safety, local employment, cultural heritage and corruption. Further, the social impact groups suggested in the guidelines are: human rights, working conditions, health and safety, cultural heritage, governance and socioeconomic repercussions. However, guidelines did not clarify the level of relationship between these social impact groups with stakeholder categories or subcategories (UNEP, 2009).

Further UNEP (2012) suggest that the basic procedure of an LCA that inherits the four-phase method ISO (2006b) can be implemented also in S-LCA. Depending on the study, data inventory can be done in two different or consecutive levels. In generic study, data covering international, national and/or sector is used for assessment of generic product chains. In the case of a specific study, focusing actual product chain for a specific product, the main data sources are interviews and site investigation (Benoît-Norris et al., 2011). Benoît Norris et al. (2013) has proposed methodological worksheet for social data collection. Social data can be available in the form of shared databases such as social hotspot database (SHDB) which is available for generic type of study (Norris et al., 2011). Several social indicators (both quantitative and qualitative) are considered to measure the social impacts associated to an intervention. The indicators used in current practice of S-LCA have been developed by different actors/stakeholders having different purposes. When it comes to impact assessment and aggregation, guidelines do not specify any impact assessment method in case of S-LCA (UNEP, 2012). However, two types of methodological approaches (performance reference point and impact pathways) for social life cycle impact assessments (S-LCIA) are distinguished by Chhipi-Shrestha et al. (2015). Focus of ‘performance reference point’ method is on living and working conditions of stakeholder (mainly workers). It covers indicators such as if there is forced labor, child labor, discrimination and freedom of association or collective bargaining. The second group of S-LCIA 'impact pathways methods' includes the methods that assess the social impacts on cause-effect pathways in the perspective of midpoint and/or endpoint indicators similar to environmental LCA (Parent et al., 2010). Interpretation of results from S-LCA is still tricky. There is a need to make results more understandable but less uncertain (Sala et al., 2015).

2.2.4 Life cycle sustainability assessment (LCSA)

The unique origin of LCA only considers environmental or ecological aspects. Later, LCA broadened itself from simply an environmental LCA to a more comprehensive life cycle sustainability assessment (LCSA). This augmentation of environmental LCA to LCSA draws on three-pillar (or triple bottom line, TBL) definition of sustainability. Thus, this new form of life cycle thinking considers environmental, economic and social impacts of product systems along their life. LCSA helps value chain performers and enterprises in becoming more accountable. It improves decision making quality by considering the complete range of impacts associated with products and services. It increases the awareness on sustainability concerns and helps in recognizing weaknesses and enabling further improvements of a product life cycle (Guinee et al., 2010; UNEP, 2012).

Defining the LCSA is under progress and a standard definition of LCSA is yet not established (Guinée, 2016). Initially, Zhou et al. (2007) used the term LCSA in their study for sustainability assessment of fuels. Soon after, Klöpffer and Renner (2008) proposed a theoretical formulation of life cycle sustainability assessment (LCSA) and stated it as:

LCSA = LCA + LCC + S-LCA

Afterward, Guinee et al. (2010) and Heijungs et al. (2010) established a broader view of the subject, providing a general overview of possibilities in LCSA. Their study focused on connecting the broadened picture of LCSA with modelling frameworks considering normative and empirical aspects. In a recent study, Guinée (2016) analyzed and reviewed studies on LCSA, published over the past half-decade, and did a brief questionnaire to scholars and experts. The analysis revealed three main conceptual developments of LCSA in comparison to environmental LCA are: (1) broadening of impacts, (2) broadening level of analysis, (3) deepening the scope of mechanisms. The challenges highlighted to the LCSA in this study are as follow:

- the requirement for more practical studies of LCSA
- effective methods to communicate LCSA outcomes
- the requirement for developing quantifiable and real indicators for S-LCA and
- sound and practical ways to deal with uncertainty assessment.

2.3 Sustainability and energy production

In this modern era, the world has become strongly conscious of the environment's limited aptitude to encourage the wide development of humanity. Human health and quality of life are significantly influenced by climate change, and pollution of air, water and soil (Kan et al., 2012; Maxim, 2014). Energy sector is a large contributor to global environmental degradation due to intensive use of fossil fuel. Studies show that CO_2 emission related to energy will cause a 3.6°C increase in average temperature over the long period (IEA, 2012). The solution is not to restrict the expansion of energy sector but to establish a balance between economic growth, quality of life and the consumption of natural resources. Thus, the goals and progress of worldwide governing authorities is tightly connected to energy demand (Breeze, 2014). Energy in the form of electricity production has central importance in the overall growth of a nation and in a life cycle perspective, sustainability issues related to energy production have been studied in various developed as well as developing countries.

Table 2.1 summarizes a total of 161 indicators that are used in 29 different studies of different regions throughout the world to study the sustainable energy production. The reviewed studies, published during years 2002-2017, reflect the accumulated knowledge of last 15 years. The synthesized indicators are grouped into 11 sustainability issues covering the three generalized groups of sustainability; environment, techno-economy and socio-political.

Table 2.1 Energy sector sustainability issues and indicators

Sr No.	Sustainability Issue	Indicator	Country/Region	Reference
		Environment		
1	Emission to air, water and soil	GWP; Ozone depletion; Acidification; Eutrophication; Photochemical oxidant creation; Freshwater, Marine and Terrestrial ecotoxicity; NMVOC, Particulate matter and Mercury emissions; Ecotoxicity; Air pollution; Hydrocarbons accidental spills; Emissions of several pollutants; Radioactivity (impact of radon); TOPP; Water quality; Winter smog; Ecological impact of zinc; Smog; Threatened species; Ionizing radiation (Total=23)	UK, Germany, Australia, Singapore, Austria, Spain, Portugal, Mexico, India, Indonesia, Mauritius, Turkey, US, Poland, Iran and Lithuania	Gagnon et al. (2002); Góralczyk (2003); Hirschberg et al. (2004); May and Brennan (2006); Kannan et al. (2007); Chatzimouratidis and Pilavachi (2009); Evans et al. (2009); Genoud and Lesourd (2009); (Kowalski et al., 2009) (Schenler et al., 2009) (Albo et al., 2010) (Carrera and Mack, 2010) (Gujba et al., 2010)
2	Resource consumption	Water consumption; Uranium energy depletion; Exergy destruction; Use of abiotic resources (elements and fossil fuels) (Total=5)	UK, Germany, Australia, Singapore, Austria, Spain, Portugal, Mexico, India, Indonesia, Mauritius, Turkey, US and Poland	
3	Land use and quality	Land occupation; Change in unprotected ecosystem area; Greenfield land use; Biodiversity; Land contaminations; Percentage effective land use; Urban land occupation; Natural land transformation; Land use competition (Total=9)	UK, Germany, Spain, India, US and Iran	
4	Waste related issues	Recyclability of input materials; Chemical, Hazardous solid, Non-hazard solid and Total waste; Treatment of waste; Critical waste confinement time; Waste repository (Total=8)	UK, Germany, Australia, Spain and Lithuania	
5	Others	Energy payback ratio; Compliance with local natural conditions (Total=2)	Iran and Lithuania	
		Techno-Economic		
1	Financial	Economic dispatchability; Capital, O&M, Fuel, Annualized, Marginal, Decommissioning, External, and Total levelized costs; Financing risk; Fuel price sensitivity; Financial incentives and assistance; Value added; Capital inclusive value added; Cost benefit index (CBI); Payback period; Profitability index (Total=17)	UK, Germany, Australia, Singapore, Austria, Mexico, Turkey, US, Iran and Lithuania	

2	Operability	Capacity and Availability factor; Technical dispatchability; Technological lock-in; Time to plant start-up from start of construction; Flexibility; Availability and technological limitations; Efficiency of energy generations; Renewability; Electrical generation potential; Per capita generation; Equivalent inertia; Auxiliary consumption; Technological competitiveness, Reliability, Innovativeness and Advantage; Durability of technology; Dependency to foreign electrical and Mechanical technology; Maturity in engineering and management activities; Lifetime of global fuel reserves at current extraction rates (Total=22)	UK, Germany, Austria, US, Iran and Lithuania	(Rovere et al., 2010) (Dorini et al., 2011) (Stamford and Azapagic, 2011) (Stamford and Azapagic, 2012) (Meyar-Naimi and Vaez-Zadeh, 2013) (Garcia et al., 2014) (Maxim, 2014) (Santoyo-Castelazo and Azapagic, 2014) (Brizmohun et al., 2015) (Hanafi and Riman, 2015) (Klein and Whalley, 2015) (Shah and Unnikrishnan, 2015) (Atilgan and Azapagic, 2016) (Li et al., 2016) (Štreimikienė et al., 2016) (Rodríguez-Serrano et al., 2017)
		Socio-Political		
1	Employment	Direct, Indirect and Total employment (direct + indirect); Average job income level; Job seasonality; Qualified manpower (Total=6)	UK, Germany, Australia, Austria, Turkey, US, Mexico, Iran	
2	Health and safety	Worker fatalities; Human toxicity potential; Worker human health impacts and Total human health impacts from radiation; Fatalities due to large accidents; Mortality; Maximum credible number of fatalities per accident; Worker injuries; Toxin release; Carcinogenic and Non-carcinogenic; Respiratory effects (Total=12)	UK, Germany, Australia, Spain, Mexico, India, Indonesia, Mauritius, Turkey, US and Iran	
3	Security and reliability of energy resources	Geo-political factors; Amount of imported fossil fuel potentially avoided; Diversity of fuel supply mix; Fuel storage capabilities; Proliferation; Diversity of technologies; Potential and effects of terrorism; Security and reliability of energy provision; Technology's autonomy (dependence on resource provision); (Total=10)	UK, Germany, Austria, EU, Mexico, Turkey, Iran and Lithuania	
4	Political and institutional stability and legitimacy	Fuel autonomy; Percentage of imported inputs; Private participation in total system; Political conflict, participation and stability and legitimacy; Governance; Immunity to terrorism and obstructionism; Compliance with international obligations; Legal regulation of activities; Support of government institutions political organizations; Influence on sustainable development of energy (Total=12)	Germany, EU, Mexico, Iran and Lithuania	
5	Quality of life and local community impact	Proportion of staff hired from local community; Spending on local suppliers; Direct investment in local community; Involvement of countries in the life cycle with known corruption problems; Volume of radioactive waste to be stored; Volume of liquid CO2 to be stored; Noise; Visual amenity; Adaptability; Perceived risk normal operation and Accountability; Landscape; Displacement (of people and animals); River damage; Odor; Notion of public good; Use of local energy resources; Regional self-determinacy; Social cohesion; Social justice; Ecological justice; Social and individual risks; Production of good and services; Quality of life; Intergenerational issues; Labor rights; Human rights; Community infrastructures; Fuel Poverty; Influence on social welfare; Influence on sustainable development of society (Total=31)	UK, Germany, Austria, EU, Mexico, Iran and Lithuania	
6	Others	Bird strike risk; Seismic activity; Transport Modeling (Total=3)	Not Specified	

Though there are some indicators that can be placed in more than one sustainability issues, they are categorized as per relevance and convenience. For example, human toxicity potential can be used to examine both health and safety issue as well as emissions to air, water and soil (May and Brennan, 2006; Stamford and Azapagic, 2012). For this research, it has been included in the health and safety issue. Another example is abiotic resource depletions which can be related to both environmental and social sustainability (Albo et al., 2010; Stamford and Azapagic, 2012). There are some indicators that show overlapping and are expressed explicitly or grouped into a common indicator or vice versa. For example, ecotoxicity potential of fresh and marine waters feeds into water quality indicator. Another example is levelized cost which is calculated by adding capital, operational and maintenance (O&M) and fuel costs (Gujba et al., 2010).

Environmental sustainability related to power generation has been summarized in four major issues as emissions to air, water and soil, resource consumption, land use and quality, and waste related issues (Atilgan and Azapagic, 2016; Rovere et al., 2010; Schenler et al., 2009). Global warming potential (GWP) is the top most consideration of environmental sustainability and more than 80% studies have discussed it. Other mostly considered indicators associated with the issue of emission to air, water and soil are acidification, eutrophication, ozone depletion and water and terrestrial ecotoxicity. Abiotic depletion of fossils and elements, and water consumptions are the mostly studied indicators under the umbrella of resources consumption issue. Land occupation or land requirement is another mostly assessed indicator which is considered in 44% of reviewed articles.

Related to techno-economic sustainability, the indicators are listed under two main groups as financial and operability issues (Chatzimouratidis and Pilavachi, 2009). Capital cost, levelized cost, capacity and availability factors, and energy efficiency are the most prominent indicators for techno-economic criteria of sustainability. The third dimension of SD is socio-political which is sub grouped as employment, health and safety, security and reliability of energy resources, political and institutional stability and legitimacy, and quality of life and local community impact (Carrera and Mack, 2010; Meyar-Naimi and Vaez-Zadeh, 2013; Stamford and Azapagic, 2011; Štreimikienė et al., 2016). Socio-political sustainability is measured by a large variety of indicators. Most of these indicators are qualitative in nature such as indicators related to political stability & legitimacy and quality of life issues. However, such indicators are less frequently considered in past studies. Whereas, quantitative indicators such as direct and indirect jobs, human health impact, worker injuries and fatalities are the top most measures to assess social sustainability. Security and reliability of energy resources is another frequently stressed area to assess social sustainability of energy production (Carrera and Mack, 2010; Santoyo-Castelazo and Azapagic, 2014).

2.4 Energy production in Pakistan

The electricity supply industry of Pakistan has a semi-public/semi-private market structure. The electricity generation in Pakistan embraces three major entities. Among these, two vertically integrated public entities are Water and Power Development Authority (WAPDA) and K-Electric. WAPDA covers entire country except Karachi and its surroundings which are solely facilitated by K-Electric. Third one is Pakistan Atomic Energy Commission (PAEC) that operates the country’s nuclear plants. Due to major inefficiencies and failure to fill the gap between the supply and demand of power and to step up the performance of power sector, National Electric Power Regulatory Authority (NEPRA) was formed under a regulatory law named ‘The Regulation of Generation, Transmission and Distribution of Electric Power Act-1997’. This authority has challenging charter to work as an independent official and devise a transparent, economically dynamic, competitive power sector in Pakistan (Kessides, 2013; Samad et al., 2016). Power wing of WAPDA is further split into vertically and horizontally structures constituting of four Generation Companies (GENCOs), the National Transmission Dispatch Company (NTDC), and nine Distribution Companies (DISCOs). Pakistan Electric Power Company (PEPCO) was established to oversee the performance of these 14 corporates and transform them into commercially viable enterprises. Later, PEPCO's functions were transferred to NTDC (NEPRA, 2015; Samad et al., 2016).

Despite these changes, the power sector is still facing darker outcome due to the trivial negligence. The country's electricity demand is growing at a rate of 11% annually, while increase in production is very low. This shortage of electricity has become one of the key issues of Pakistan (Lodhi and Malik, 2013; Sakrani et al., 2012). Initiatives are taken and authorities are showing their interest to cater for this issue in the form of energy summits and long debates over ways to address electricity shortages (Kessides, 2013). Pakistan's energy policy requires an integrated, systematic and economically-wide approach. It should represent adequate trade-offs between regulatory, energic, economic and environmental aspects (Qudrat-Ullah, 2015). This research will help policy makers to develop and improve energy production keeping in view the sustainability development. In three-dimensional view of sustainability, selected indicators will furnish a life cycle evaluation of energy production in the country.

2.4.1 Power generation-mix in Pakistan

As per (NEPRA, 2015), the total nominal power generation capacity of Pakistan as on 30th June, 2015 was 24,823 MW; of which 16,814 MW was thermal, 7,116 MW was hydroelectric, 787 MW was nuclear and 106 MW was wind as graphically shown in Figure 2.4

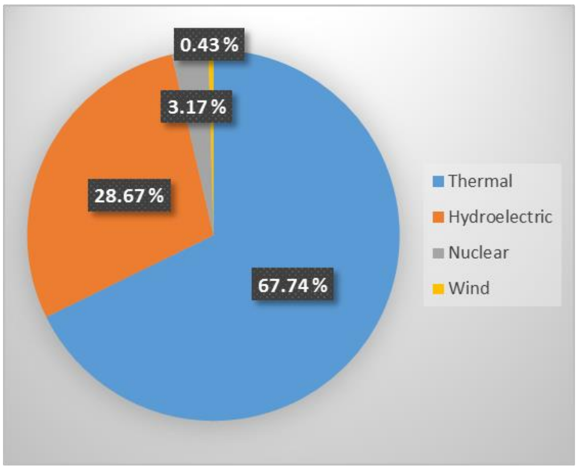


Figure 2.4 Capacity for each technology

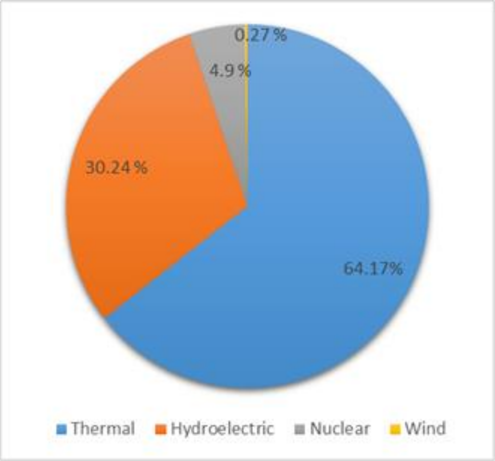


Figure 2.3 Power generation 2014-2015

During 2014-15, the total energy generated in the country was 109,059 GWh of which the share of thermal electricity generation was 69,988 GWh (64.17%), hydel power plants were 32,979 GWh (30.24%), nuclear power plants were 5,349 GWh (4.90%) and wind power plant was 300 GWh (0.27%) as shown in Figure 2.3. Due to largest share of thermal power generation sector in Pakistan depends heavily on fuel-oil imports. Pakistan was self-reliant in natural gas but with economic growth, urbanization, and conversion of thousands of transportation vehicles from fuel-oil to Compressed Natural Gas (CNG) the GOP needed to import the natural gas, as well.

Chapter 3

RESEARCH METHODOLOGY

3.1 Background

Literature review provides an overview and evolution of sustainability assessment in life cycle perspective. Further relation of SD with energy production and the need of improvement in sustainable energy production in Pakistan is highlighted. In effort to fulfil this need, research methodology will help to achieve the objectives of this research.

Research methodology is a body of knowledge which enables researchers to explain and analyze methods, indicating their limitations and resources, identifying their presuppositions and consequences and relating their potentialities to research advances (Miller and Salkind, 2002). Appropriation between research paradigm, type of data and collection methods has significant implications upon the research findings. Detailed methodology of this research which is used to achieve the objectives set forth in chapter 1 is discussed in this chapter.

3.2 Research design

Assessment of the sustainability of electricity sector in Pakistan involves five core steps. First, the goal and scope of this study are defined and then, through literature review, sustainability indicators are selected based on the most prominent SD issues in energy sector. After the life cycle sustainability inventory in third step, the forth step encompasses assessment of different electricity options considering environmental, economic and social aspects of sustainability in a life cycle perspective. Finally, the most sustainable electricity generation options for Pakistan have been identified based on a comparative analysis of all operational alternatives and sustainability score measured by multi-criteria decision analysis (MCDA). The methodology framed for this study is shown in Figure 3.1, with detailed description of key steps in subsequent sections.

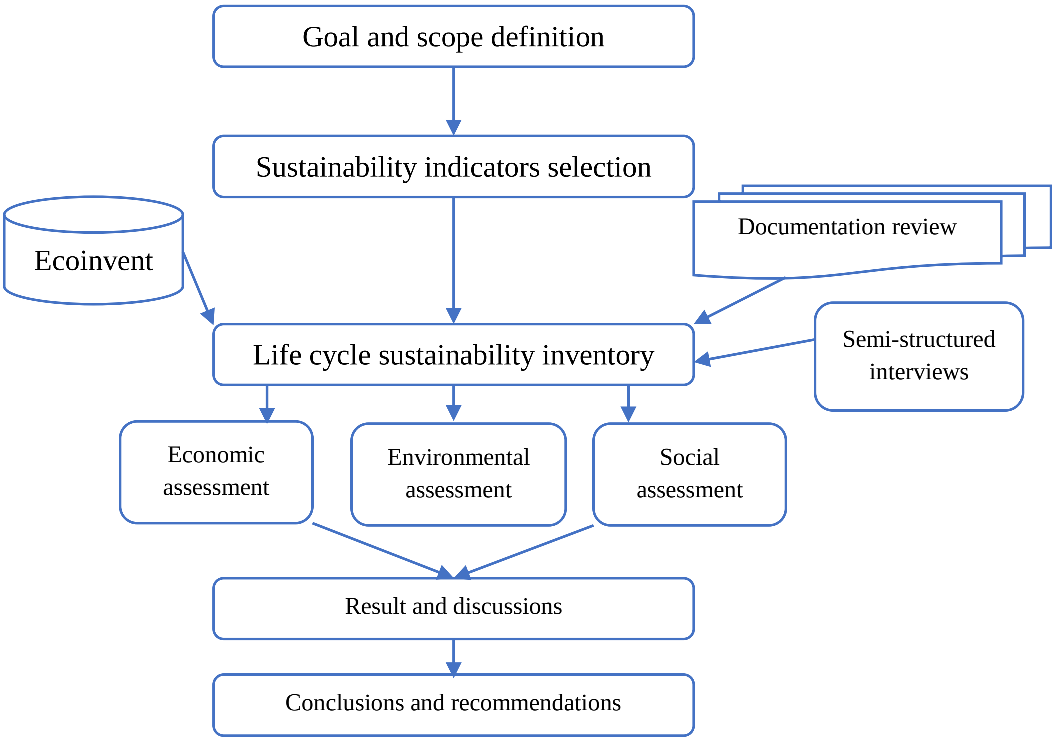


Figure 3.1 Research methodology for sustainability assessment of electricity sector in Pakistan

3.2.1 Goal and scope of definition

The goal of this study is to assess the sustainability of energy sector in Pakistan in terms of economic, environmental and socio-political impacts of different electricity production sources currently available by applying a typical life cycle approach. The findings of this study will provide a new line of thinking and knowledge horizon for policy makers and stakeholders to enhance the performance of electricity sector in the country.

The functional unit is an essential element of life cycle assessment to measure the quantified performance of a product or service and most importantly it provides basis for comparison of results (Jönsson, 2000; Mithraratne et al., 2007). In various studies synthesized in Table 2.1, the mostly used functional unit for assessing the sustainability of power generation is 1 KWh of electricity generation and same is used in this study.

The life cycle assessment can be performed with multiple scopes including cradle to cradle, cradle to grave and cradle to gate (Filimonau, 2016). For this research, the scope is limited to *cradle to gate* and the assessment is performed with respect to raw materials and fossil fuel extraction and transportation (where relevant), along with the construction and operation of power plants as shown in Figure 3.2. Transmission and distribution of electricity are outside the scope of this research and therefore not considered in the study.

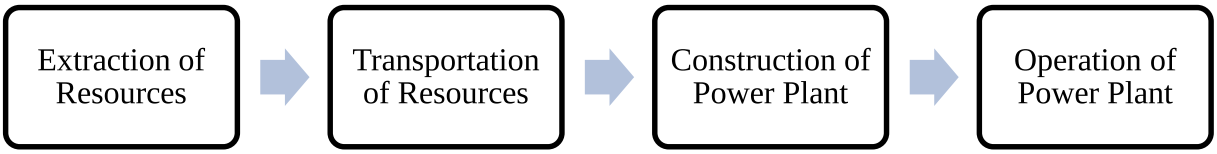


Figure 3.2 Generic system boundary defining scope of study

3.2.2 Sustainability indicators selection

In this study sustainability indicators have been identified and selected based on the globally accepted sustainability issues related to electricity generation and particularly in context of the Pakistan power sector. Extensive literature has been consulted from which a total of 29 most relevant taxonomies were reviewed to identify the highlighted sustainability issues and indicators as shown in Table 2.1. After identification of 161 indicators, they are further categorized based on environmental, techno-economic and socio-political issues. Based on the available data and categorizations, 20 indicators for this research have been selected considering the global acceptance along with appropriateness for local energy sector as shown in Table 3.1

Table 3.1 Sustainability indicators for current study

Sr No.	Name	Unit of measure	Description
Environmental indicators (Based on CML-IA (v.3.03) impact assessment method)			
1	Abiotic resource depletion elements	kg Sb eq./kWh	Represents depletion of minerals and metals. The Abiotic Depletion Factor (ADF) is determined for each extraction of minerals (kg antimony used equivalents/kg extraction) based on concentration reserves and rate of de-accumulation.
2	Abiotic resource depletion fossil	MJ/kWh	This measure of depletion of fossil fuels in a product system.
3	Global warming	kg CO_2 eq./kWh	This measure of climate change because of different greenhouse gases (GHGs) emissions.
4	Acidification potential	kg SO_2 eq./kWh	This represents the contribution of acidifying substances such as sulfur dioxide (SO_2), NOx and ammonia (NH_3) to the potential acid deposition in air, water or soil.
5	Eutrophication potential	kg PO_4 eq./kWh	This refers to potential of excessive levels of macro-nutrients to cause overfertilization of water and soil, which causes an increase in growth of biomass (algae).
6	Fresh water ecotoxicity	kg DCB eq./kWh	This indicator measures the impact on fresh water ecosystems because of emissions of toxic substances to air, water and soil.
7	Human toxicity	kg DCB eq./kWh	This indicator represents the effects of toxic substances on the human environment because of their emission in air, water and soil
8	Marine water ecotoxicity	kg DCB eq./kWh	It is referring to impacts of toxic substances on marine ecosystems
9	Ozone layer depletion	kg CFC-11 eq./kWh	This indicates the potential of emissions of chlorofluorohydrocarbons (CFCs) and other halogenated substances to deplete the ozone layer. Thus, UV-B radiation reaches the earth surface and this can have harmful effects
10	Photochemical oxidants	kg C_2H_4 eq./kWh	This is related to the formation of reactive substances, potential of volatile organic compounds (VOCs) and nitrogen oxides (NOx) generates photochemical or summer smog.

11	Terrestrial ecotoxicity	kg DCB eq./kWh	This category refers to impacts of toxic substances on terrestrial ecosystems
			Economic indicators
1	Capital Cost	PKR/KW	Capital costs represent the sum of all the costs required to construct and install power plants, initial capital expense for equipment and installation
2	Total Annualized Cost	PKR/Year	Sum of annualized capital (incurred with capital costs and annuity factor), annual fixed, annual variable (operation and maintenance costs) and annual fuel costs.
3	O&M Costs	PKR/Year	-
4	Fuel Cost	PKR/Year	-
5	Levelized Cost	PKR/KWh	The costs per unit of electricity generated (total annualized costs divided by annual electricity generation)
			Social indicators
1	Direct Employment	Job-Years/TWh	Direct employment (ED) in a system is the sum of the employees actively working in each subsystem.
2	Total Employment	Job-Years/TWh	This includes direct plus indirect employment in life cycle of product system
3	Imported fossil fuel avoided	Koe/KWh	Related with the amount of imported hard coal and gas that is to be combusted to provide an equivalent amount of electricity from technologies which do not depend on imported fossil fuels
4	Supply risk	Ranking value (0-1)	How safely and easily fuel resources are accessible

Further, the assessment of environmental sustainability is carried out using CML-IA (v.3.03) method that has 11 baseline indicators (Goedkoop et al., 2016; Guinée, 2001). CML is the most commonly used life cycle impact assessment (LCIA) method (ISO, 2000a), having a global database, transparency and lesser uncertainty of results as compared to other available impact assessment methods such as TRACI (Bare, 2002), RECIPE (Goedkoop et al., 2009) and Eco-Indicator 99 (Goedkoop and Spriensma, 2000). Faculty licensed SimaPro 8.2.3.0 (PRé, 2016) software is used for carrying out LCA. In addition, to address the concerns of economy, a total of five indicators of capital, O&M, fuel, total annualized and levelized costs are considered. The assessment and estimation of these indicators is based on the methodology adopted from Santoyo-Castelazo and Azapagic (2014) and Stamford and Azapagic (2011).

The third dimension of SD is assessed through social welfare which is considered as one of the leading development goals for any society. Establishing the judgement of social impacts and benefit is very difficult and is principally argued because the perception of social issue largely depends on cultural norms, different ethics, and societal lifestyles (Sala et al., 2016). Because of this broadened boundary, literature reports many indicators to assess the socio-political dimension of power generation. But, in this study, due to less developed methodology and data constraints, only four indicators are considered related to employment and energy security issues.

3.2.3 Life cycle sustainability inventory

For life cycle sustainability inventory of different electricity options as well as the overall electricity-mix of Pakistan, data have been collected from three main sources; Ecoinvent, documentation review and semi-structured interviews as shown in Figure 3.1. Year 2015 is selected as base year, since ample data is available for this year. Also, annual averages for base year 2015 are considered and any variations in the fuel mix and operational parameters that may occur during the year are ignored. Further, life time of different technologies is assumed from IEA et al. (2015) and Wernet et al. (2016).

Pakistan has seven main sources of electricity generation and total of 77 major power plants are operational in country as shown in Table 3.2. All these sources are considered in this study. For simplification purpose, electricity generation with Bagasse is substituted with same amount of generation with natural gas due to its very small contribution of 0.26% to the national grid. Whereas, sustainability assessment of power generation from coal, despite its very little input (0.19%) to national grid, is performed since national energy policies and visions stress to increase production capacity of coal up to 7000 MW, constituting more than 15% of future energy mix (PC, 2014). The data related to thermal power plants operating on more than one fuel source are considered and analyzed with respect to primary fuel.

Table 3.2 Electricity mix of Pakistan as per NEPRA (2015)

Technology	**Total Plants** (NOs)	**Capacity (2015)** (MW)	**Annual Generation (2015)** (GWh)	(%)
Hydropower				
Reservoir	07	5,061	23,652	21.69
Run of River (RoR)	17	2,055	9,327	8.55
Thermal				
Gas	30	65,00	31,196	28.60
Oil (FO + HSD)	17	10,164	38,690	35.48
Coal	01	150	102	0.09
Nuclear	03	787	5,349	4.90
Import	-	-	443	0.41
Wind	02	106	300	0.28
Total	**77**	**24,823**	**109,059**	

Furhter details on the assumptions and data collection with respect to major sustainability dimensions for different electricity technologies are provided in the following sections.

3.2.3.1 Data collection and assumptions related to enviromental sustainability

The inventory of data and the assumptions related to environmental sustainability for different technologies are summarized in Table 3.3. Ecoinvent 3.3 database is the main source of background life cycle inventory (LCI) (Wernet et al., 2016). The data related to fuel consumptions and composition

Table 3.3 Summary of life cycle inventory data and assumptions

Reservoirs	RoR	Wind	Oil	Natural gas	Coal	Nuclear	Source
Life time of constructed facility (in years):							
150	80	20	30	30	30	40	(IEA et al., 2015; Wernet et al., 2016)
Ecoinvent-Plant capacity (MW):							
Average size: 175.6	Average size: 8.6	Offshore: 2	500	Combined cycle: 400	100	PWR: 650	(Flury and Frischknecht, 2012; Wernet et al., 2016)
Transport of fuel and resources (Distance in Km):							
Lorry: 250	Lorry: 250	Lorry: 300 Train: 200	Indigenous Pipeline = 1,350 Country Ship Lorry Afghanistan 0 450 Belize 17,200 750 Kuwait 2,100 550 Malaysia 5,000 500 Oman 885 1,000 Saudi Arabia 4,100 1,200 Singapore 5,400 500 UAE 1,300 750	Indigenous Pipeline: 7,500	Lorry: 25	Air: 2,000 Ship: 250	On Assumptions and (Google Maps, 2017; NEPRA, 2017; SR, 2017)
Fuel consumption:							
N/A	N/A	N/A	FO: 0.2133 Kg/KWh HSD: 0.0192 Kg/KWh	0.337 m^3/KWh	1.482 Kg/KWh	30000 MWD/T	(MPNS, 2016; NEPRA, 2007; NEPRA, 2015; Wernet et al., 2016),
Net heating value (NHV):							
N/A	N/A	N/A	FO: 43 MJ/Kg HSD: 46.5 MJ/Kg	33.53 MJ/m^3	(12.79-21.30) MJ/Kg	(500-650) GJ/kg	(JICA and HBP, 2015; MPNS, 2016; World Nuclear Association WNA, 2017)

Fuel composition:							
N/A	N/A	N/A	Sulphur content (%) Furnace oil (FO): 3.5 High speed diesel (HSD): (0.5-1)	Natural gas sui and other fields: (mole-%): Methane (88.852) Ethane (5.148) Propane (0.257) Butane and heavier (0.183) Nitrogen (4.815) Carbon Dioxide (0.745)	Lakhra coal-lignite (%): Ash (4.3-4.9) Sulfur (1.2-14.8) Moisture (9.7 -38.1) Volatile matter (18.3- 38.6) Carbon (9.8-38.2)	Slightly Enriched Uranium UO_2: (%) (2.4 - 3)	(Azam, 2008; JICA and HBP, 2015; NEPRA, 2017; Wernet et al., 2016; Yasin et al., 2012),
Thermal Efficiency:							
N/A	N/A	N/A	28.22-43 (%)	24.84-37.5 (%)	17.74 (%)	N/A	(NEPRA, 2014; NEPRA, 2015; NEPRA, 2017)
Direct emissions:							
N/A	N/A	N/A	(CO_2, SO_2, CO, CH_4, N_2O, NO_x, NMVOC)			N/A	(NEPRA, 2017; Wernet et al., 2016)

are Pakistan specific and gathered from Azam (2008), JICA and HBP (2015), MPNS (2016) and Yasin et al. (2012). Along with using Ecoinvent, data related to direct emissions from power plants is collected through field surveys and license agreements of generation companies (NEPRA, 2017; Wernet et al., 2016). Computation of transportation values of primary fuels and resources from extraction sites to power plant is carried out through Google Maps (2017), NEPRA (2017) and PPIS (2014).

Maximum effort has been put to collect data specific to Pakistan but due to time and scope limitations and unavailability of data, wherever appropriate, Ecoinvent database has been used and scaled using ‘economies of scale’ approach (Atilgan and Azapagic, 2016; Coulson et al., 1993). For example, in case of construction of hydropower plants, Ecoinvent data has been used and environmental impact has been scaled using the relation given in Equation 3.1, where I_1 and I_2 represent the impact, and C_1 and C_2 represent the capacity of larger and smaller plants respectively.

$$I_2 = I_1 \times \left\{\frac{C_2}{C_1}\right\}^{0.6} \qquad \textbf{Equation 3.1}$$

3.2.3.2 Data collection and assumptions related to economic sustainability

Economic data related to three key indicators of capital, O&M, and fuel costs are gathered through secondary sources such as annual reports, online sources and financial statements of different organizations and authorities such as Water and Power Development Authority (WAPDA), Private Power & Infrastructure Board (PPIB), National Electric Power Regulatory Authority (NEPRA), FFC Energy Limited and others.

Capital cost estimation for reservoir is based on 100% of projects while in case of RoR power plants, total capital investment estimation is based on 8 projects having a total capacity of 1713 MW or 83% of total available capacity (WAPDA, 2015; WAPDA, 2017). The capital costs for thermal and wind power projects are taken from (NEPRA, 2015; NEPRA, 2017; PPIB, 2014).

The estimation is based on total 33 projects consisting of 100% coal projects, 90% gas projects, 64% oil projects and 100% wind projects installed in Pakistan. There are three nuclear power plants in country and capital cost estimation is based on the two projects sourced from IBP (2013) and World Nuclear Association WNA (2017). O&M costs for base year 2015 for thermal power projects are estimated from 32 projects, contributing 57312 GWh that is 80% of total thermal power generation (NEPRA, 2015). O&M costs of hydropower projects running under WAPDA is 11240 MPKR (110 US$) (WAPDA, 2015). It is assumed that these costs are dispersed to reservoirs and RoR facilities with respect to their weighted average generation and capacity of two technologies. O&M costs for wind power generation is considered from FFCEL (2017). Due to lack of data in case of nuclear source, it is assumed that nuclear power plants have same O&M costs per KWh of generation as those of gas power plants. Annual fuel costs for both nuclear and fossil fuel are sourced through NEPRA (2015).

The capital cost in commissioning year is brought to base year (2015) using consumer price indices (CPI) of Pakistan as provided by world bank for year 1960 to 2015 with CPI (2010 = 100) and for base year CPI (2015 = 145.30) (WB, 2016). The discounting rate used for the calculation of the annualized capital cost is 10% commonly applied in electricity sector (IEA et al., 2015).

3.2.3.3 Data collection and assumptions related to socio-political sustainability

For social sustainability, employment is assessed with respect to four main sectors as extraction of primary fuels (where relevant), manufacturing, construction and installation, and operation of plants. Jobs in the first two sectors provide an estimate of the indirect employment and for last two sectors, govern direct employment associated with power generation (Atilgan and Azapagic, 2016; May and Brennan, 2006). For thermal power plants, operational stage jobs are estimated as per NEPRA (2015) while for other life cycle stages, employment factor has been estimated by multiplying regional-adjustment factor of Pakistan based on non-OECD (Organization for Economic Cooperation and Development) Asia region with that of OECD countries (Rutovitz et al., 2015). Jobs during construction and operation for RoR hydropower plants is based on primary data collected for four power plants. Owing to the lack of data, employment in other technologies has been estimated by applying regional-adjustment factor for Pakistan to employment factor of OECD, and China and India, where relevant. For example, manufacturing stage jobs for nuclear power plants are based on China as all power plants are manufactured there (NEPRA, 2017; Rutovitz et al., 2015). The estimated employment factor for different technologies during life cycle are presented in Table 3.4.

Table 3.4 Employment factors in different life cycle stage of facilities

Life Cycle Stage	Unit of Measure	Oil	Gas	Coal	Reservoir	RoR	Nuclear	Wind
Construction	job-years/MW	1.97	3.12	26.9	17.8	26.3	28.3	17.1
O&M	jobs/MW	0.63	0.91	2.63	0.48	0.43	1.44	0.48
Manufacturing	job-years/MW	2.25	2.25	14.0	8.40	26.2	3.38	28.6
Extraction of Fuel	jobs/PJ	15.1	15.1	6.10	N/A	N/A	0.003	N/A

Since non-renewable resources largely account for electricity mix, energy security has emerged as one of the major sustainable issues (MOF, 2016) and evaluated based on two indicators. Firstly '*imported fossil fuel potential avoided'* is the equivalent amount of fossil fuels that is to be imported and combusted to provide an equivalent amount of electricity from technologies which do not depend on imported fossil fuels. The second indicator '*diversity of fuel supply mix'* is used to assess the reliance on countries of fuel supply chain. Estimation methodology of these two indicators is common to Atilgan and Azapagic (2016) and Stamford and Azapagic (2012). To estimate the imported fossil fuel potentially avoided, efficiency of the fossil fuel fleet has been taken as the average of different oil-fired power plants (36%) as given in Table

3.3. Since Pakistan is self-sufficient in coal and gas generation, *diversity of fuel supply mix* has been calculated only related to oil and nuclear fuel. Quantities of oil domestically produced and imported during year-2015 from different supplier countries have been source from MPNS (2016) and PBS (2016) as shown in Table 3.5.

Table 3.5 Fuel oil supply (2015)

Fuel Oil (Tons)	
Domestic	3,485,045
Imported	
Afghanistan	104
Belize	1,110
Kuwait	3,637,676
Malaysia	141,736
Oman	84,909
Saudi Arabia	408,913
Singapore	1,656
United Arab Emirates	4,148,029
Total	**11,909,178**

3.2.4 Determination of sustainability score

Sustainability score for each option is measured using MCDA with the help of weighted aggregated function adopted from Díaz-Balteiro and Romero (2004) as given in Equation 3.2, where S_s represents overall sustainability score of each option (0-1), w_i is the considered weight of indicator or dimension *i* of sustainability and v_i is normalized value or performance of an option on indicator or dimension *i* of sustainability.

$$\boldsymbol{S_s = \sum_{i=1}^{n} w_i v_i} \qquad \textbf{Equation 3.2}$$

Chapter 4

RESULTS AND DISCUSSIONS

This chapter presents results on sustainability assessment of electricity mix of Pakistan and comparison of seven options for power generation in a life cycle perspective. Full results for each operational technology and the indicators are provided in Table 4.1. Firstly, economic sustainability is discussed followed by the environmental and socio-political sustainability.

4.1 Environmental sustainability assessment

Environmental sustainability of electricity sector of Pakistan has been assessed using LCA approach. Environmental impact comparison of different sources per unit of electricity generation is shown in Figure 4.1. The eleven indicators shown in this figure can be associated with different environmental issue highlighted in Table 2.1.

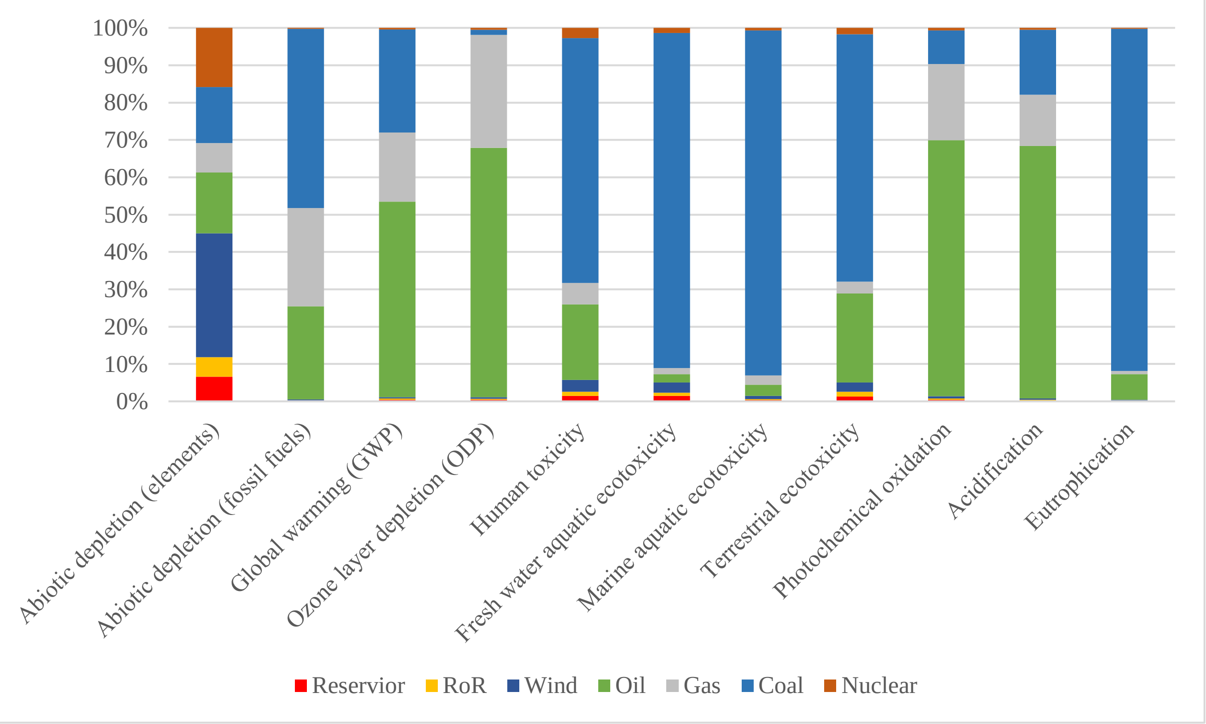


Figure 4.1 Environmental impact comparison per KWh

Table 4.1 Results and findings of study

Sr No.	Indicators Names	Unit of Measure	Reservoir	RoR	Wind	Oil	Gas	Coal	Nuclear	Electric mix
Economic										
1	Capital costs	PKR/KW	134,443	193,781	279,485	151,619	149,690	200,110	189,063	152,846
2	O & M costs	PKR/KWh	0.350	0.357	1.835	0.390	0.239	0.195	0.239	0.330
3	Fuel costs	PKR/KWh	-	-	-	12.89	4.85	4.50	1.55	6.04
4	Total Annualized Costs	MPKR/year	76,363	43,169	3,814	618,278	320,006	3,550	24,477	1,089,657
5	Levelized cost	PKR/KWh	3.23	4.63	12.71	15.98	10.26	34.80	4.58	10.03
Social										
1	Direct Employment	job-years/TWh	150	155	411	172	341	1,995	281	222
2	Total Employment	job-years/TWh	173	227	815	320	512	2,635	446	345
3	Imported fossil fuel avoided	Koe/KWh	0.166	0.166	0.166	-	0.166	0.166	0.166	0.158
4	Diversity of fuel supply mix:	Score (0-1)	1	1	1	0.7	1	1	0 or 1	0.84-0.89
Environmental										
1	Abiotic depletion (elements)	ug Sb eq/KWh	56.96	45.49	285.80	139.95	68.19	129.72	136.27	93.37
2	Abiotic depletion (fossils)	MJ/KWh	0.09	0.08	0.13	13.36	14.09	25.73	0.13	8.86
3	Global warming (GWP)	g CO$_2$ eq/KWh	12.83	8.78	11.38	1502.86	531.00	790.11	12.51	692.78
4	Ozone layer depletion (ODP)	ug CFC-11 eq/KWh	1.01	0.77	0.90	161.66	73.14	3.40	1.22	78.94
5	Human toxicity	g DCB eq/KWh	21.72	15.25	46.59	292.30	83.49	947.91	39.16	137.09
6	Fresh water ecotoxicity.	g DCB eq/KWh	26.77	16.00	49.96	39.61	30.66	1634.78	25.13	33.03
7	Marine water ecotoxicity	kg DCB eq/KWh	16.38	12.02	34.65	130.57	108.21	4023.88	29.68	87.53
8	Terrestrial ecotoxicity	g DCB eq/KWh	0.06	0.05	0.11	1.01	0.13	2.82	0.07	0.42
9	Photochemical oxidation	mg C$_2$H$_4$ eq/KWh	2.79	2.42	4.30	459.14	136.87	60.20	4.68	203.97
10	Acidification	mg SO$_2$ eq/KWh	41.73	35.46	65.54	12456.88	2525.90	3207.02	94.54	5182.71
11	Eutrophication	mg PO$_4$ eq/KWh	14.81	13.90	28.58	847.18	105.11	11337.25	29.46	348.56

The comparison of production mixes of Pakistan with other countries is shown in Figure 4.2. As there is high pressure on stakeholders regarding GWP (Iqbal et al., 2010), this indicator under a distinct issue named climate change is discussed separately followed by resource depletion and other environmental impacts. Other detailed results are provided in Table 4.1.

4.1.1 Climate change

With respect to climate change, hydropower is the most sustainable option since both RoR and reservoir have the lowest GWP as 8.78 and 12.83 g CO_2-eq/KWh respectively. Due to large direct emissions during plant operation, oil-fired power plants are the worst with emission of 1,502.86 g CO_2-eq/KWh. Despite low range transportation, coal is the second worst option with 790.11 g CO_2-eq/KWh due to lower efficiency. Overall GWP of energy production in Pakistan is 692.78 g CO_2-eq/KWh. Putting this figure into perspective of total national production, 75.25 Mt CO_2-eq. is emitted in year-2015 with 77.3% and 22 % contribution from oil and gas-fired power plants as simulated by SimaPro and shown in Figure 4.3.

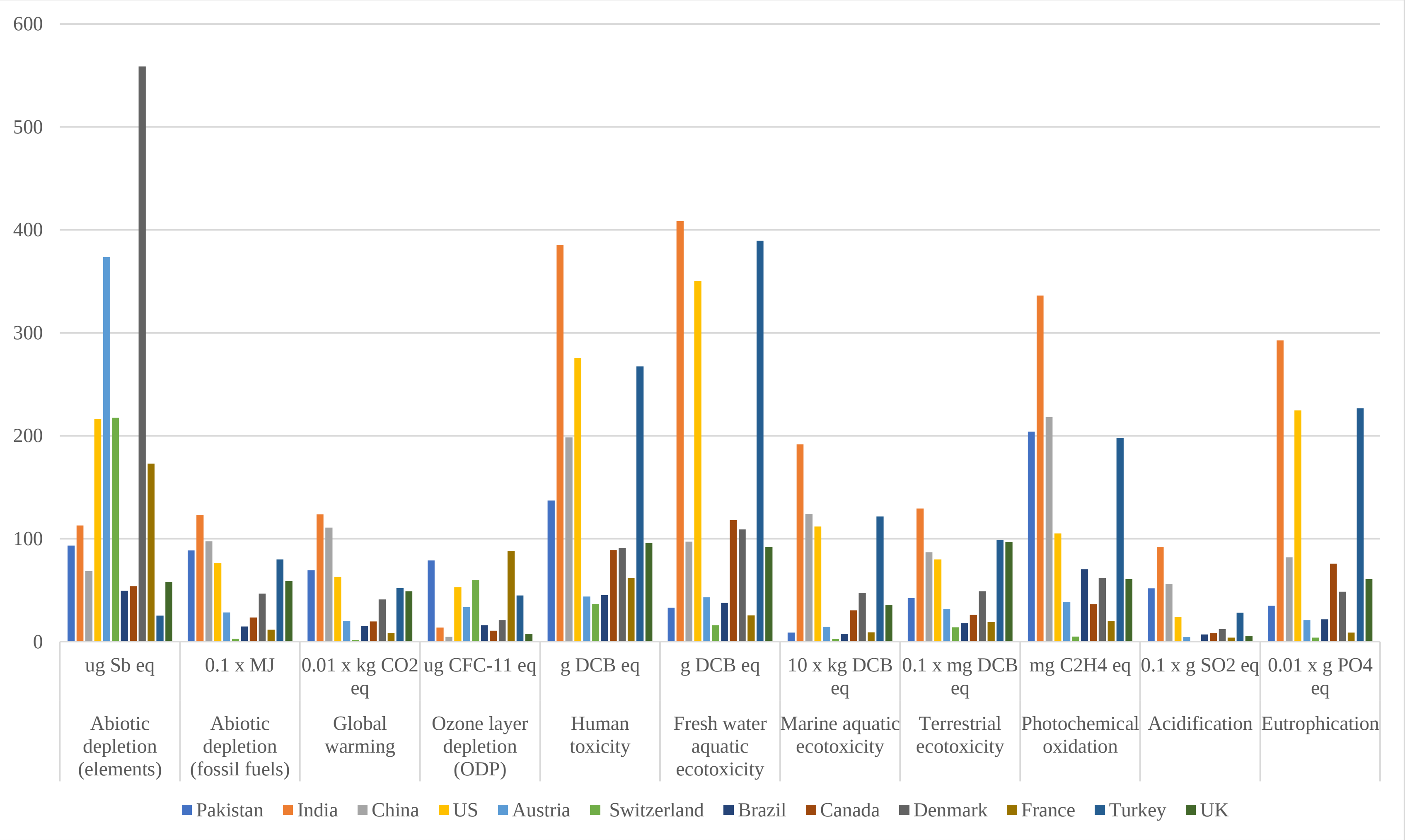


Figure 4.2 Comparison of environmental impacts of various countries [Expressed per KWh] (Atilgan and Azapagic, 2016; Stamford and Azapagic, 2012; Wernet et al., 2016)

This impact is relatively low as compared to neighbouring countries of India (1,238 g CO_2-eq/KWh) and China (1,109 g CO_2-eq/KWh) where coal is a far larger source of electricity production with total contribution of over 70%. Similarly, the countries that have large contribution of thermal generation such as USA (630 g CO_2-eq), Turkey (523 g CO_2-eq) and UK (490 g CO_2-eq) and show highest GWP per unit (KWh) generation of electricity (WB, 2017).

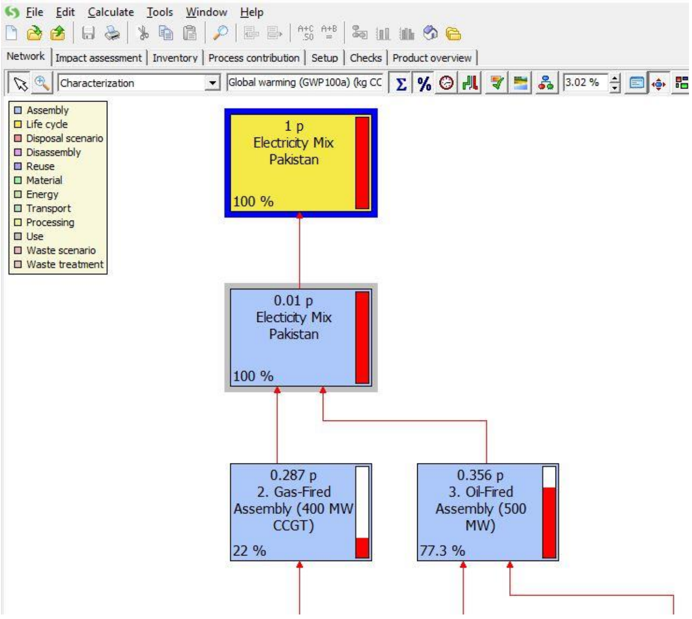


Figure 4.3 GWP for Electricity Mix of Pakistan (SimaPro 8.2.3.0)

4.1.2 Resource consumptions (ADP elements and fossil)

Research findings show that in case of ADP elements, wind consumes higher resources in its total life cycle as 285.80 ug Sb eq/KWh, mainly due to extensive use of metals and metalloids in power plant construction. Oil and nuclear are second and third most impactful options consuming 139.95 and 136.27 ug Sb eq/KWh of element resources. Like GWP, hydropower is the best option in this case with use of 45.49 ug Sb eq/KWh and 56.96 ug Sb eq/KWh for RoR and reservoir options respectively. In context, comparing with other countries, as shown in Figure 4.2, consumption of element resources is lowest for electric mixes with high percentage of hydro, gas or coal plants such as Turkey (25 ug Sb eq/KWh), Brazil (49 ug Sb eq/KWh), Canada (54 ug Sb eq/KWh), UK (58 ug Sb eq/KWh), China (69 ug Sb eq/KWh) and Pakistan (93 ug Sb eq/KWh). On the other hand, countries that have higher share of renewable (wind and solar) and nuclear power plants like Denmark (559 ug Sb eq/KWh), Switzerland (217 ug Sb eq/KWh), US (216 ug Sb eq/KWh) and France (173 ug Sb eq/KWh) show high ADP of elements (Atilgan and Azapagic, 2016; Stamford and Azapagic, 2012; WB, 2017; Wernet et al., 2016).

ADP fossils is highest for thermal power plants with 13.36, 14.09 and 25.73 MJ/KWh for oil, gas and coal respectively. Due to very low efficiency of 17.4% of coal plants, depletion of coal is the highest for Pakistan as compared to UK and Turkey where a consumption of 15.1 MJ/KWh is reported. Since fossils extraction is the single distinct contributor to this impact, the ADP fossils in case of renewable and nuclear technology sum up to only 0.43 MJ/KWh. In similarity with Pakistan, it is obvious that countries with high reliance on thermal resources like India (82%), Turkey (79%), China (75%), USA (68%) and UK (61%) consume high fossils resources.

4.1.3 Other environmental impacts

Life cycle impact of other eight environmental indicators, in consequence of emissions to air, water and soil, is discussed in this section with detailed results in Table 4.1. It is very clear from these findings that hydro, wind and nuclear are the most sustainable options in these impact categories.

In terms of ozone layer depletion potential (ODP), oil and gas are the least environmentally sustainable options with 161.66 and 73.14 ug CFC-11 eq/KWh respectively. In case of oil, about 90% of ODP is due to emissions of halon products during oil production and for gas, main contribution is from transportation of resources. A total of 7.31 ug CFC-11 eq/KWh of

ODP is made up of remaining options. Similarly, oil and gas are also the lowest sustainable option for and photochemical oxidation potential with impacts estimated at 459.14 and 136.87 mg C2H4 eq/KWh respectively.

Further, human toxicity potential which is mostly considered indicator for health and safety issue as shown in Table 2.1 is assessed as about 947.91 g DCB eq/KWh due to emissions of heavy metals to air, water and soils during mining of coal. This is about 3, 11, 20 and 62 times the impact caused by oil, gas, wind and RoR. In fresh and marine water aquatic ecotoxicity potentials coal is the worst sustainable options with impacts of 1634.78 and 4023.88 g kg DCB eq/KWh respectively. These toxicity potentials are due to large discharge of heavy metals to water. Other worse options are oil, gas and wind respectively.

The indicator of terrestrial ecotoxicity potential shows the same behavior as those of fresh and marine water aquatic ecotoxicity potentials. Here too coal is the least sustainable option followed by oil and gas with impact of 2.82, 1.01 and 0.13 g DCB eq/KWh respectively. RoR and reservoir with potentials of 0.05 and 0.06 g DCB eq/KWh are the best options.

Because of high Sulphur content of up to 3.5%, as shown in Table 6, oil is the worst option in case of acidification potential with a value of 12456.88 mg SO_2 eq/KWh. Coal and gas are at second and third position with impact of 2525.90 and 3207.02 mg SO_2 eq/KWh. With a value of 11337.25 mg PO_4 eq/KWh, generation with coal is worse for eutrophication potential. Emission of phosphates during mining of coal contributes for 90% of this impact during that life cycle stage. With an impact of 847.18 mg PO_4 eq/KWh oil is the second least sustainable option for eutrophication. Like other indicators of emissions to air, water and soil issue, hydropower is the most sustainable options for both of acidification and eutrophication potentials.

Comparing the impacts of electricity mixes of different countries, it is difficult to project a specific pattern due to different plant technologies, quality of fuel and other factors. However, countries that depend mostly on thermal power such as India, China, USA, Turkey and UK show higher impacts for human, terrestrial, and fresh and marine water ecotoxicity potentials. Further, highest impacts of acidification and eutrophication potentials for India China and USA can be associated with highest contribution coal as a source of electricity production.

4.2 Economic sustainability assessment

As discussed earlier seven indicators are estimated to assess techno-economic aspect of power generation in Pakistan. Over all result shows that power generation with hydropower plants are most economic while coal costs the most due to very low efficiency and operability of current working plants. Nuclear is at third place followed by gas, wind and oil. A more detailed discussion of these results is given in following sections for different options and electricity mix.

4.2.1 Capital cost

Pakistan's electricity mix has capital cost of PKR 1,52,846 (US$ 1,502)/KW. Highest costs for construction and installation of plant is for wind power plants as PKR 2,79,485 (US$ 2,746)/KW followed by coal power plant is PKR 2,00,110 (US$ 1,966)/KW (NEPRA, 2015; NEPRA, 2017). The capital costs are lowest in case of reservoir and gas power plants as PKR 1,34,443 (US$ 1,321)/KW and PKR 1,49,690 (US$ 1,471)/KW respectively. Based on these data, total capital of 24,823 MW installed capacity for year-2015 is 3.794 trillion PKR (US$ 37.3 billion) having 67% of thermal, 28% of hydro, 4% of nuclear and 1% of wind facilities.

4.2.2 Total annualized cost

Total annualized cost is calculated by adding annualized capital cost for year-2015, O&M costs and fuel costs during same year using similar methodology as used by Atilgan and Azapagic (2016). Estimated annual costs of electricity production during 2015 was PKR 10,89,657 million (US$ 10, 705 million)/year. Percentage share of different sources in this annual cost of electricity is as shown in Figure 4.4.

Annual cost of power production with oil is maximum due to its largest contribution to generation and highest fuel cost. Power production with gas imposes 30% of total annual cost. Share of hydro-electric to annual cost is 11% even though its contribution toward national production is 30% as shown in Table 3.2. This difference is due to zero fuel and lower O&M costs.

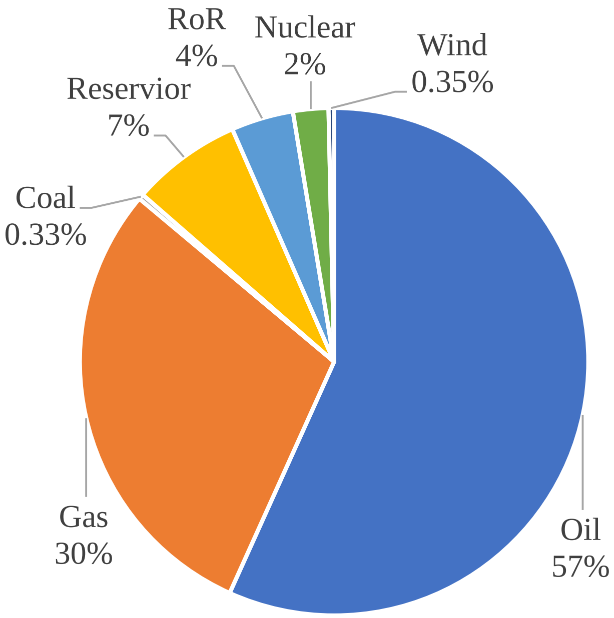


Figure 4.4 Annual cost of electricity generation (year-2015)

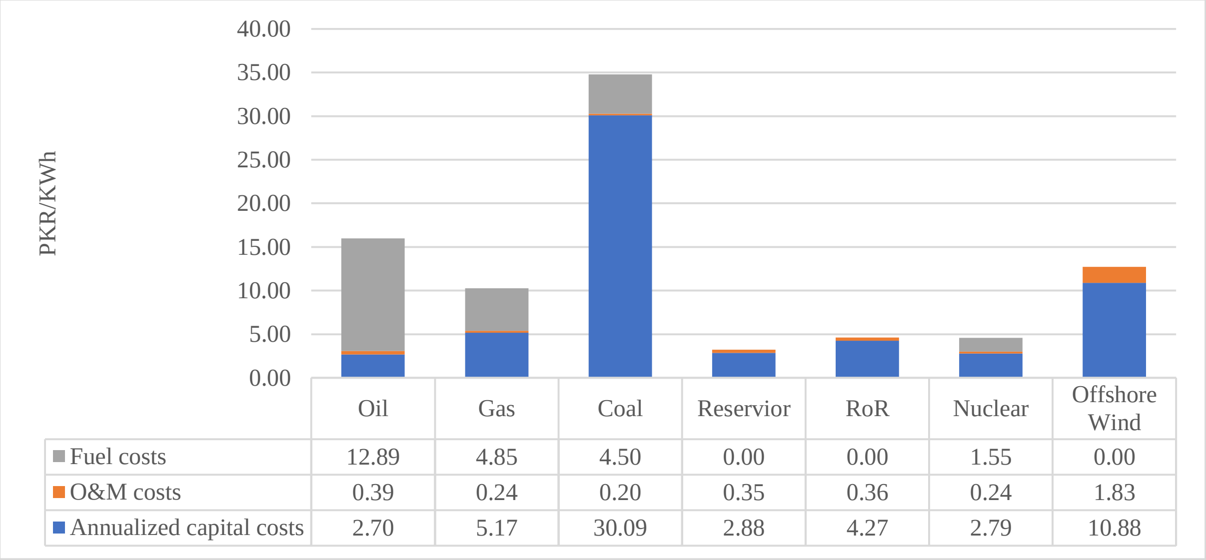
4.2.3 Levelized cost

To view the cost of each option in life cycle costing perspective, levelized cost of electricity generation has been estimated in base year-2015 adopting similar methodology of Atilgan and Azapagic (2016) as per the formula given in $LC = \frac{AC_t}{G_a}$ Equation 4.1, where LC represents levelized cost of electricity generation (PKR/KWh), AC_t is the total annual cost of electricity generation (MPKR/year) and G_a is the annual electricity generation (GWh/Year).

$$LC = \frac{AC_t}{G_a} \qquad \textbf{Equation 4.1}$$

Base on the levelized cost of each option and their contribution to the national grid, overall unit cost of electricity mix is estimated as 10.03 PKR/KWh (US$/MWh 98.5). For context, cost of unit generation as per NEPRA and Government of Pakistan (GOP) tariff varies between PKR 4 to 19 depending on the number of units of consumption and for purpose such as residential or commercial (NEPRA, 2015).

Contribution of different costs to the levelized cost for different electricity technologies is presented in Figure 4.5. The results highlight that electricity from reservoir is the most economic and low-priced (3.23 PKR/KWh), followed by RoR (4.63 PKR/KWh) and nuclear (4.58 PKR/KWh). Due to very low efficiency (17.74%) and operability of coal power plants currently operational, the country is bearing highest cost for unit electricity generation with coal as 34.79 PKR. Due to highest fuel cost, generation with oil is second costly option (15.98 PKR/KWh) for current electricity mix of Pakistan.



	Oil	Gas	Coal	Reservior	RoR	Nuclear	Offshore Wind
■ Fuel costs	12.89	4.85	4.50	0.00	0.00	1.55	0.00
■ O&M costs	0.39	0.24	0.20	0.35	0.36	0.24	1.83
■ Annualized capital costs	2.70	5.17	30.09	2.88	4.27	2.79	10.88

Figure 4.5 Contribution of different costs to the levelized costs for various electricity technologies

A comparison of unit cost of electricity generation in other developed and under developing countries is shown in Figure 4.6 based on similar studies (Atilgan and Azapagic, 2016; Gujba et al., 2010; Santoyo-Castelazo and Azapagic, 2014; Stamford and Azapagic, 2012).

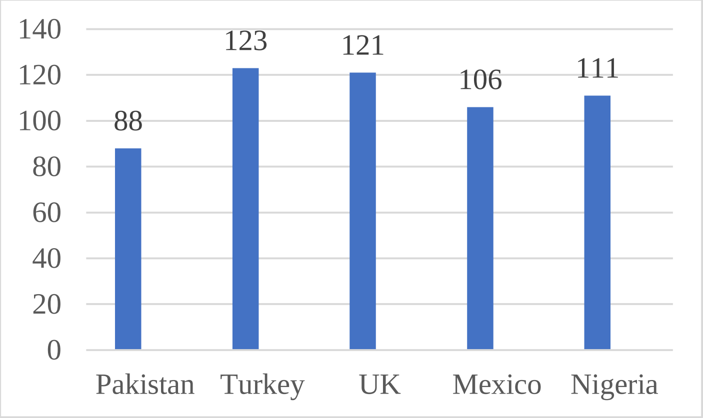


Figure 4.6 Levelized cost of electricity generation in different countries (US$/MWh in year-2012)

The difference in the costs is mainly due to the differing electric-mix and plant technologies in these countries. Further, unit cost of electricity generation in Pakistan is the least among these countries mainly due to a large share of 30% of relatively low cost options (hydropower) as compared to 2%, 24.6 %, 13.5 % and 0 % in UK, Turkey, Mexico and Nigeria respectively

(Atilgan and Azapagic, 2016; Gujba et al., 2010; Santoyo-Castelazo and Azapagic, 2014; Stamford and Azapagic, 2012).

4.3 Socio-political sustainability assessment

As already stated that due to data constraints, only four relevant indicators has been evaluated to assess social sustainability of power production in Pakistan. Results show that life cycle employment is highest for generation with coal and wind power plants while lowest in case of reservior and RoR. The detailed evaluation of these indicators is given in following sections.

4.3.1 Employment

In this study, direct employment refers to the jobs during construction and operational stages of power plants without including jobs during decommissioning of plants (May and Brennan, 2006). Table 4.1 reports that direct-employment is highest in case of coal power plant as 1995 jobs-years/TWh. Though the level of employment is high, it is not necessarily encouraging since these plants operate at very low efficiency (17.74%) as compared to other technologies (NEPRA, 2015). The second highest jobs related to construction and operation is provided by offshore wind as 411 jobs-years/TWh followed by generation with gas power plants as 341 jobs-years/TWh. For this indicator, generation with hydro-power plants is least sustainable option with 150 jobs-years/TWh and 155 jobs-Years/TWh for reservoir and RoR respectively. The reason for this low employment associated with hydropower plants is due to their higher capacity factor with an average of 86% (NEPRA, 2015). The overall direct employment associated with electricity sector of Pakistan is 222 jobs-years/TWh providing a total of 24,112 jobs in year-2015 with a contribution of 44% of gas, 28% of oil and 15% of reservoir power plants.

Total employment is the sum of direct and indirect employment. As already stated, indirect employment is associated with jobs during extraction of fuel and manufacturing of power plants. The pattern of total employment is same as that of direct employment, that is the largest share is provided by generation with coal as 2635 jobs-years/TWh, which is due to a large contribution of direct-employment of about 76%. Again, offshore wind and gas-fired power plants are second and third sustainable options while RoR and reservoir plants have the lowest total employments as 815, 512, 227 and 173 jobs-year/TWh respectively. Summing these results, electricity mix of Pakistan provides a total employment of 345 jobs-years/TWh, and during year-2015 this sector provided a total of 37,473 jobs.

Comparing the findings of this study with other two studies that follow same methodology to conclude total employment of electricity mix, it is found that high employment associated with power generation of Pakistan as compared to total employment of Turkey (270 jobs-years/TWh) and UK (123 jobs-years/TWh) is due to low labour productivity and GDP of Pakistan (Atilgan and Azapagic, 2016; Stamford and Azapagic, 2012).

4.3.2 Energy security

Energy security is an important issue for power sector of Pakistan (MOF, 2016). As already stated that generation with gas and coal is based on indigenous supply of fuel, this issue has been evaluated based on the generation with fuel oil and nuclear fuels. It is estimated that technologies which do not depend on the imported fossil fuels, such as coal, gas, nuclear and renewable technologies, avoid 0.158 Koe per unit of electricity generation (KWh). In other words, on annual basis, these technologies substitute the import of fossil fuel equivalent to 17.27 Mtoe. Due to difference in efficiency of power plants and electricity mix, fossil fuel avoided in UK and Turkey is 0.0506 Koe/KWh and 0.072 Koe/KWh respectively (Atilgan and Azapagic, 2016; Stamford and Azapagic, 2012).

The second indicator that is *diversity of fuel supply* has been computed based on similar formula as adopted by Stamford and Azapagic (2012) and Atilgan and Azapagic (2016) which uses

Simpson's Diversity Index (Simpson, 1949). Performance of this indicator relies on two major aspects of indigenous fuel production and dependence on different supplier countries. Thus, it can be improved by generating more fuel indigenously and importing from more countries or demoting dependence on one or two major suppliers (Stamford and Azapagic, 2012). The results show that score of oil supply is 0.7, the index is high due to non-reliance on one or two suppliers as shown in Table 3.5. In case of supply for nuclear technology, data for fuel import is not available; however, the impact of nuclear fuel import on overall fuel supply index is very low due to low contribution to the national grid. In case if all nuclear fuel is produced indigenously, that is if score is 1, then the value of overall index will be 0.89. On the contrary, if worse condition is assumed, that is 0 score for nuclear fuel supply, then the overall index drops to 0.85. This shows a very low impact of nuclear fuel supply. By comparison, the total diversity index for UK and Turkey is 0.82 and 0.72 respectively (Atilgan and Azapagic, 2016; Stamford and Azapagic, 2012).

4.4 Sustainability scores

To identify or highlight the most sustainable options, sustainability scores have been evaluated using MCDA and results are shown in Figure 4.7 Sustainability score based on equal weight to all sustainability dimensions. Using $\boldsymbol{S_s = \sum_{i=1}^{n} w_i v_i}$ Equation 3.2, equal weighting has been given to each sustainability dimension. Since each dimension has been covered with the help of various indicators, to obtain effective solution and avoid selection bias in results, equal importance to each constituent indicator has been given.

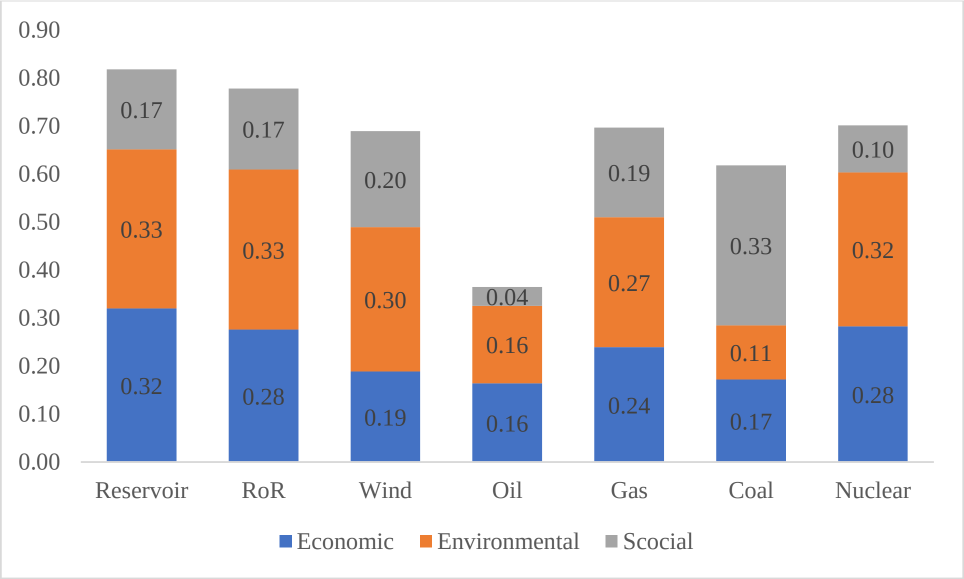


Figure 4.7 Sustainability score based on equal weight to all sustainability dimensions

It has been found that hydropower is the best sustainable option for Pakistan with sustainability score of 0.82 and 0.78 for reservoir and RoR technology respectively which is mainly due to major economic and social contributions. Nuclear has little difference and stands as the third most sustainable option with a score of 0.70. Oil-fired power is the least sustainable option with a score of 0.36. The second least sustainable option is coal with substantial difference from oil-fired power with a score of 0.62.

Comparing individual sustainability dimensions, hydropower and nuclear are highly economically sustainable. And as obvious, renewable sources of hydropower and wind are most environmentally sustainable options. Due to higher global warming human, terrestrial, and fresh and marine water ecotoxicity potentials, coal power is the least environmentally sustainable. Due to energy security issue, oil has least score of 0.04 in social sustainability.

Chapter 5

CONCLUSIONS AND RECOMMENDATION: POLICY GUIDELINES

SD is vital for the evolution of generations, and the energy sector having a major contribution to SD should be effectively assessed and managed to accomplish the fruits of sustainable energy production. Various sustainability issues have been identified and addressed all over the world to achieve sustainable energy production. It is the need of hour for developing countries like Pakistan to develop effective and sustainable energy policies. To meet this need, the current study has conducted an integrated sustainability assessment of the electricity sector in Pakistan, reflecting all the power plants and currently operational generation technologies. This is the first time that a life cycle evaluation of each technology has been performed on 20 sustainability indicators embracing all main dimensions of SD.

The findings illustrate that the overall cost per unit of generation is PKR 10.03/KWh (US$ 98.5/MWh) which annually accounts up to PKR 1,089,657 million (US$ 10,705 million) with 87% and 11% shares of thermal and hydropower. More than 80% of environmental impacts of energy sector are caused by thermal power plants with an annual GWP of 75.25 Mt CO2-eq. The assessment of social sustainability signifies that around 37,473 jobs were provided by this sector during year 2015. The social sustainability is highly affected by energy security because of fuel oil import with the diversity of fuel supply index equal to 0.70. Further, in year 2015, a total of 17.3 Mtoe was avoided by renewable and technologies that do not depend on imported fossil fuels.

Comparing the individual technologies with respect to considered sustainability indicators, hydropower, both reservoir and RoR, is the most preferred source due to the lowest economic and environmental impacts. But its preference is compromised due to its least life cycle employment potential. It is further revealed that wind is the worst option for capital investment in Pakistan, unlike Turkey where it has an acceptable initial cost. Irrespective of coal and gas, importing of fuel makes the oil a worst option for energy security. Overall in six environmental indicators, coal is the worst option for electricity generation. Even a relatively higher employment potential cannot save coal due to lower efficiency which also results into higher cost per unit. Gas power plants have a negative relationship with GWP and ozone layer depletion, however their capital investment is relatively attractive. Like hydropower, nuclear imposes the least impact on economic and environmental concerns.

These results are likely to lead the stakeholders to opt for the most sustainable option in the light of their viewpoint and associated importance of different sustainability dimensions. However, by assuming equal importance for these aspects, it is found that hydropower is the most sustainable option for Pakistan while oil is the least. Further, based on these results, following policy guidelines and recommendations are concluded for stakeholder, and national and regional authorities.

- Recent energy policy focuses on fulfilling the shortfall while attuned to safeguarding the environment. A wider view on environmental, economic and social impacts covering life cycle of plants is needed to avoid solving one issue at the expense of another. This will help in making the most sustainable and long-term decisions.
- Assessment of technological and political stability of energy sector is needed to get more transparent and effective solutions in policy making.
- Energy production with oil should be gradually reduced to cover the load of energy security and high cost of electricity per unit generation. But this should be done keeping in view the demand and supply, and political and social emphasis of independent power producers (IPPs).

- Pakistan has large potential of hydropower production with respect to both small and large power plants. Current policies aim to tap this source and many projects are under construction or planning. This could be a plus point related to environmental and economic aspects but social aspects like public acceptance, relocations, wild life issues, quality of life, land transformations and water supply should be adequately and properly addressed.
- Future policy goals show an interest to increase production with coal (up to 15%) (PC, 2014). This addition must be done keeping in view the environmental impacts due to emissions and energy security risk due to fuel supply. Technological advancements in plants are vital since low efficiency severely impacts the economy and environment. For example, if current efficiency of plants is improved from 17.4% to 40%, the GWP and cost will go down up to 3 times.
- By improving the issues related to health and safety, and nuclear proliferation, the positive impacts on environmental and economic sustainability will drive an increase in nuclear based production.
- Increment in production with renewable (wind and solar) sources should be done with proper trade-offs between cost, element resource depletion and other environmental issues.
- National and regional authorities, and R&D institutions should support research in life cycle thinking and SD covering the techno-economic, environmental and socio-political dimensions to bring long-term effective solutions.

This study is based on the sustainability assessment of electric-mix in Pakistan for the base year of 2015 and has considered different technologies currently operational. Data and scope limitations, and constraints may impose uncertainty in results and further improvements can be brought using more transparent, complete and region-specific data on environmental and social aspects. Also, since transmission and distribution of electricity were outside the scope of this research, future studies can benefit from including these critical network operations to obtain holistic assessment. Another limitation of this research is its equal treatment of sustainability dimensions and indicators in assessing overall sustainability score. Due to resource constraints, authors resorted to using equal weights but future studies may engage the key stakeholders involved in policy- and decision-making to attain a sophisticated decision support system.

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