A renewable electricity supply system in Pakistan by 2050: assessment of generation capacity and transmission system requirements

A Dissertation Presented

By

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Dedication

With love and best wishes to my children……
Muhammad Aashir Noor Afridi (Son)
and
Aayesha Noor Afridi (Daughter)

Table Contents

Glossary and Abbreviations/ Acronyms

[n.d]: n.d means "no date", the acronym can be found in the citation and reference of a website/source, when the date is not mentioned in the article/information.

[online]: This is used in the place of a page number in the citations and references when a piece of information is taken from an online source (i.e., website).

[n.p]: n.p means "no paginations", In some documents, the page numbers are not mentioned. The acronym will be written in such cases.

Table: In some reports or documents, data are presented in tables (i.e., as annexes having no page number). In this case, the table number has been referred to in the citation and the references.

Note: In the text of the thesis, the word "TABLE" is referred to as being plural while for "FIGURE", both singular (i.e., figure) and plural (i.e., figures) can be found. Similarly, the word DATA is considered plural, while INFORMATION is used both singular.

ASDC. Atmospheric Science Data Center
ADB. Asian Development Bank
AEDB. Alternative Energy Development Board
AEMO. Australian Energy Market Operator
AHGI. Available Horizontal surface Global Insolation
AJ&K. Azad Jammu and Kashmir
AUF. Annual Utilization Factor
BAU. Business As Usual
BCM. Billion Cubic Meter
BEPC. Basin Electric Power Cooperative
BHGI. Blocked Horizontal surface Global Insolation
CASA. Central Asia-South Asia
CCS. Carbon Capture and Sequestration
CHP. Combined Heat and Power
CIDA. Canadian International Development Agency
CPGCL. Central Power Generation Company Limited
DLR. Deutsches Zentrum für Luft- und Raumfahrt
DE. Deutschland
DGNRER. Directorate Generals of New and Renewable Energy Resources
DISCO. Distribution Company
DIW. Deutsche Institut für Wirtschaftsforschung
DK. Denmark
EFOM. Energy Flow Optimization Model
EIB. European Investment Bank
ENPEP. Energy and Power Evaluation Program
ENS. Electricity Not Served
ESMAP. Energy Sector Management Program
ETSAP. Energy Technology Systems Analysis Program
EUNA. Europe-North Africa

FATA. Federal Administrative Tribal Area
FESCO. Faisalabad Electric Supply Company
FIDA. Foundation for Integrated Development Action
GB. Gilgit Baltistan
GDP. Gross Domestic Product
GENCO. Generation Company
GEPCO. Gujranwala Electric Power Company
GHG. Greenhouse Gases
GIS. Geographical Information System
GMD. Geometric Mean Distance
GMR. Geometric Mean Radius
GMT. Greenwich Mean Time
GOP. Government of Pakistan
HDIP. Hydrocarbon Development Institute of Pakistan
HESCO. Hyderabad Electric Supply Company
HFO. Heavy Fuel Oil
HG. High Growth
HMA. Hybrid Modelling Approach
HOMER. Hybrid Optimization of Multiple Energy Resources
HPP. Hydel Power Plant
HUBCO. HUB power Company
HW_HW. How Wind - High Wastage
HW_LW. High Wind - Low Wastage
HW_HPC. High Wind - High PV Capacity
HW_LPC. High Wind - Low PV Capacity
IAEA. International Atomic Energy Agency
ICIMOD. International Centre for Integrated Mountain Development
IDA. Interesseorganisation for alle ingeniero (Danish Society of Engineers)
IEA. International Energy Agency
IEE. Initial Environmental Examination
IESCO. Islamabad Electric Supply Company
IFC. International Finance Corporation
IIASA. International Institute of Applied System Analysis
IOM. International Organization for Migration
IPCC. Intergovernmental Panel on Climate Protection
IRS. Indus River System
IRSA. Indus River System Authority
IRSD. Initiatives for Rural and Sustainable Development
IWT. Indus Water Treaty
JICA. Japan International Cooperation Agency
KESC. Karachi Electric Supply Corporation
KP. Khyber Pakhtunkhwa
kV. Kilovolt
LEAP. Long-range Energy Alternatives Planning
LESCO. Lahore Electric Supply Company
LOI. Letter of Interest
LPG. Liquefied Petroleum Gas
LW_HPC. Low Wind and High PV Capacity

LW_LPC. Low Wind and Low PV Capacity
MAF. Million Acre-Feet
MAED. Model for Analysis of Energy Demand
MCM. Million Cubic Meter
MDTF. Multi Donors Trust Fund
MHDC. Mahbub ul Haq Human Development Centre
MEPCO. Multan Electric Power Company
MESSAGE. Model for Energy Supply Systems And their General Environmental impact
MG. Moveable Gasholder
MHGI. Maximum Horizontal surface Global Insolation
MIT. Massachusetts Institute of Technology
MJ. Megajoule
MW. Megawatt
MWPD. Ministry of Water and Power Development
NA. National Assembly
NAMA. National Appropriate Mitigation Action
NASA. National Aeronautics and Space Administration
NEM. National Energy Market
NETL. National Energy Technology Laboratory
NEPRA. National Electric Power Regulatory Authority
NO. Norway
NPV. Net Present Value
NREL. National Renewable Energy Laboratory
NTDC. National Transmission and Despatch Company
OAAGR. Overall Average Annual Growth Rate
ODA. Overseas Development Agency
OG. Optimum Growth
PAGR. Population Annual Growth Rate
Pak-IEM. Pakistan Integrated Energy Model
PBS. Pakistan Bureau of Statistics
PCAT. Pakistan Council of Appropriate Technology
PCRET. Pakistan Council of Renewable Energy Technologies
PEPA. Pakistan Environmental Protection Agency
PEPCO. Pakistan Electric Power Company
PESCO. Peshawar Electric Supply Company
PHES. Pump Hydroelectric Storage
PILDAT. Pakistan Institute of Legislative Development and Transparency
PMD. Pakistan Meteorological Department
PPIB. Private Power and Infrastructure Board
PRES. Pakistan Renewable Energy Society
PWC. Pricewaterhouse Cooper
PV. Photovoltaic
QA. Quid-e-Azam
QESCO. Quetta Electric Supply Company
RCP. Representative Concentration Pathways
RE. Renewable Energy
RAEP. Renewable and Alternative Energy Association of Pakistan
RENPAS. Renewable Energy Pathways Simulation System

RHPP. Reservoir based Hydropower Plant
RORHPP. Run of River Hydropower Plant
RPM. Resources Planning Model
RSPN. Rural Support Programmes Network
RWE. Rheinisch-Westfälisches Elektrizitätswerk (Rhine-Westphalia Electric Industry)
RP. Release Percentage
SANEI. South Asian Network of Economic Research Institutes
SDPI. Sustainable Development Policy Institute
SEI. Stockholm Environment Institute
SEPCO. Sukkur Electric Power Company
SIL. Surge Impedance Loading
SODAR. Sonic Detection and Ranging
SP. Storage Percentage
SR. Spatial Resolution
SRU. Sachverständigenrat für Umweltfragen (German Advisory Council on the Environment)
SS. Seasonal Storage
TDSC. Total Discounted System Cost
TESCO. Tribal Electric Supply Company
TIMES. The Integrated MARKAL-EFOM System
UN. United Nations
UNDP. United Nations Development Program
USAID. United States Agency for International Development
UPS. Uninterrupted Power Supply
USA. United States of America
VBA. Visual Basic Application
WAPDA. Water And Power Development Authority
WASP. Wien Automatic Strategy Plans
WEC. World Energy Council
WECC. Western Electricity Coordinating Council
WMO. World Meteorological Organization
WRI. World Resource Institute
ZEPL. Zorlu Enerji Pakistan Ltd.,

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Abstract

Keywords: Pakistan, renewable electric system, renewable resources in Pakistan, hourly demand-supply modelling and simulation, energy system planning

Pakistan has substantial renewable resources in the form of hydro, solar, wind and biomass. However, only the contribution of the hydro resources is significant in the supply mix of the power system. In this research, all of the mentioned resources were considered, in order to assess a renewable electricity system in Pakistan by the year 2050. For the assessment, an approach of hourly temporal and high spatial resolutions was used to analyze the system. The approach helped in; i) incorporating the supply resources variations, ii) estimating the system infrastructure requirements, iii) and assessing the regional inter-dependency.

For analysis, the electricity demand of Pakistan was forecasted and found to be 430 TWh and 556 TWh in two different economic growth scenarios, by 2050. Each demand value was considered with four different combinations of the renewable resources. For the hourly demand-supply balance, the system was modelled and simulated in a sequential-time modelling tool. The tool was specifically developed for this purpose. From the balances, hourly inter-regional power flows were found. These flows were used to assess the maximum power flows in each corridor of the transmission system. This helped to estimate the transmission lines requirements.

The analysis showed that if the demand remains in the range of 400 TWh by 2050, the resources can conveniently fulfill it. A higher demand would have to be met by a noticeably higher supply of a seasonal storage system.

Finally, using the MESSAGE framework, the discounted system cost was calculated. The cost was based on the infrastructure (i.e., installed capacity & transmission lines) investment and system operational costs. The objective of this task was to techno-economically compare the supply combinations and find the most cost efficient one. The findings showed that using a lower (i.e., 40% of the total) wind capacity is more cost efficient in the low demand scenario. However, the difference in the costs of the cases significantly reduced when the higher value of the demand was considered. In all of the cases, the discounted system cost was in the range of 170 to 240 billion US$. The cost included both the investment and operation cost of the proposed 100% renewable electric supply system, across the period 2012-2050.

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Chapter 01: Introduction and Research Statement

In this research, the electric power system of Pakistan was analyzed with a proposed renewable supply system. This chapter briefly introduces the theme and objectives of the research. The chapter also presents the scope of the work, which can be helpful in reading the forthcoming details of the thesis. At the end, the chapter outlines the thesis layout to get an idea about the course of the details. However, the following section will first introduce, and briefly discuss, the dilemma of Pakistan's energy supply system.

1.1 Pakistan's Energy Supply System

Pakistan's commercial energy consumption grew by an annual average growth rate of 6.5% during 1947[1] to 2012 (Abbasi et al., 2013, p. 2). Meanwhile, efforts have been made to explore and exploit the indigenous energy resources. Despite the efforts, the imports of energy are about 30% (Figure 1. 1)[2] of the total consumption (Ministry of Finance, 2014, p. [Table 14.2]), (NTDC, 2013, p. 14), (HDIP, 2013, p. 04). In the imports, the major part (i.e., ~88%) is of oil (i.e., crude oil and petroleum products), in which, a significant share is used for power generation. Using oil, Pakistan generated 35.2% of the total (i.e., 95.5 TWh) gross electricity demand[3] during 2011-12 (HDIP, 2013, pp. 04, 82).

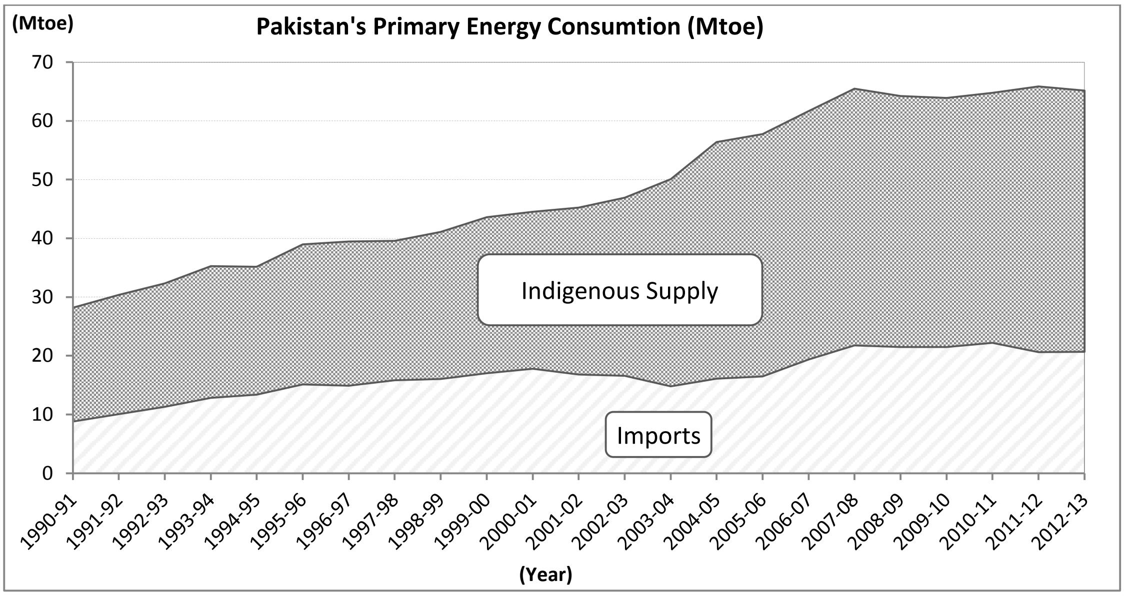

Figure 1. 1: Historical primary energy consumption in Pakistan
Source: (Ministry of Finance, 2014, p. [Table 14.2]), (NTDC, 2013, p. 14), (HDIP, 2013, p. 04)

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[1]Pakistan became Independent in 1947
[2] The shares of different resources in the current supply mix of the energy and electric power system are discussed in the upcoming chapters of the thesis.
[3] The value did not include load-shedding, which is discussed in the "Demand Forecast" chapters of the thesis

The electric supply system of Pakistan is a public entity. Therefore, the government controls and regulates the tariffs, which are generally lower than the system cost. Because of this, the system frequently needs financial support to operate at its full power capacity, particularly when oil prices are high. According to the Ministry of Finance (2014, p. 219), the government gave a total subsidy of PRs.[4] 1.7 trillion between 2003 to 2013 to the power system.

Similarly, Pakistan's indigenous natural gas resources fulfilled about 50% demand of the primary energy during 2011-12. In total, about 29% was consumed by the power generation system (HDIP, 2013, pp. 04, 82). However, the gas reserves are declining, and are assessed to be only 25-30% of the current value by the year 2027-28 (Abbasi et al., 2013, p. 5). Remarkably, despite the mentioned subsidy, the supply system is struggling to meet demand. Consequently, a significant load shedding[5] is done by National Transmission and Despatch[6] Company (NTDC) of Pakistan, to manage the system operation (NTDC, 2011c, p. 1(1)).

1.2 Research Statement

According to World Energy Council (WEC) (2013, p. 18), a growth of 123%-150% is expected in the global electricity generation by 2050 compared to 2010. To generate the needed power, the use of fossil fuels is one potential option, but concerns are growing about the future viability of fossil fuel use. In general, the consumption of the fuels emits different gases, including, carbon dioxide (CO_2) and methane (CH_4). These gases are collectively called greenhouse gases (GHG).

Using historical data, the researchers have found a correlation between the CO_2 concentrations in the earth's atmosphere and a rise in the global temperature (IPCC, 2015, p. 9). This rise in the temperature is seen as an anthropogenic input to Climate Change i.e., changes in the length of summer season, variations in the patterns and intensities of rainfalls, melting of glaciers, rise in the level of seas, etc., (IPCC, 2013, pp. 134-135, 199).

Consequently, the ongoing climate protection and mitigation efforts are focused on a significant reduction in GHG, particularly $CO_{2,}$ emissions. To reduce the emissions, one option is to increase the share of renewable resources in the supply mixes of power systems. In its fifth assessment report, IPCC suggested a substantial share of the resources by the year 2050 in the energy supply mix of the world (i.e. RCP 2.6), to achieve the 2°C global warming target by 2100 (IPCC, 2014, pp. 217,556-558). For the desired contribution, it is required to include the maximum possible capacity of the resources in the future development plans. According

[4] The US$ exchange rate during the period was about 60-95 PRs
[5] The load shedding was assessed to be ~25-30 TWh by 2012
[6] Officially written as Despatch

to Lund (Lund H. , 2010, p. 11), supply security and creation of jobs are the additional benefits of such development.

Generally, Pakistan is assisted by international funding agencies or countries in the development of power sector projects. However, the support of lenders for fossil fuel projects, particularly coal power projects, decreased due to the Climate Change issue. For example, according to the World Bank guiding principles for energy sector financing *"the World Bank Group will only in rare circumstances provide financial support for new greenfield coal power generation projects, such as meeting basic energy needs in countries with no feasible alternative "* (World Bank, 2013, p. [online]). The media recently reported that under the same principle, the bank withdrew its financial support for a coal mining project in India (The Economic Times, 2015, p. [online]). In the same context, the policy of Asian Development Bank (ADB) is relatively clear, which says, *"ADB will not finance coal mine development except for captive use by thermal power plants, and oil field development except for marginal and already proven oil fields"* (ADB, 2009, p. 04).

In contrast, there is more willingness to support renewable energy projects. For example, the World Bank is currently supporting dozens, if not hundreds, of projects relevant to the development of renewable resources (World Bank, 2016, p. [online]). These include at least one project for Pakistan with the objective of remapping the country's renewable resources (ESMAP, [n.d], p. [online]).

In Pakistan, the Energy Wing of the Planning Commission[7] is the entity, which formulates the development policies of the energy and power system. For expansion planning, the wing recently developed "Pakistan Integrated Energy Model (Pak-IEM)"[8]. The model is based on a single region concept and uses three seasonal and four daily time slots (i.e., total 12 time slices) of the demand variability (Planning Commission, 2010b, pp. 15-18). Using Pak-IEM, a study was executed to develop a future expansion plan of the system. The study considered 15% intermittent renewable resources, in the renewable scenario (i.e., group 5 scenario), by 2030 (Planning Commission, 2010a, p. 50). However, next year, NTDC considered only a 5.5% share of the intermittent renewable resources in its plan by 2030 (NTDC, 2011c, p. 6(49)).

The reasons of having limited future targets can be many, but one possible cause is the lack of knowledge and confidence regarding potential amounts of the resources. To increase confidence through knowledge, efforts are needed to depict the potential role of renewable resources. This will help decision makers to set optimal future targets for the renewable

[7] Established in the Ministry of Planning, Development and Reforms
[8] TIMES framework has been used for the modelling of the system

resources in Pakistan. This research has been carried out with the same motivation at its core. This work has assessed a possible contribution of the renewable resources, specifically in the power supply system of Pakistan. It also highlights associated challenges and opportunities to develop and operate this particular system.

1.3 Research Objectives

From the overview of the electricity supply situation and research statement, it can be concluded that the development of the renewable resources is among the promising options for Pakistan. The development can contribute towards climate protection efforts, as well as towards the reduction of the country's energy dependency. Furthermore, the country can take advantage of international support opportunities. Therefore, it was relevant to work out the renewable resources potential contribution, in Pakistan's power supply system.

The main objective of this research was to assess the adequacy of the resources for a proposed 100% renewable electric supply system by 2050. More specifically, the research focused on infrastructure requirements, including generation capacity and transmission lines. Due to these efforts, a demand-supply model was also developed, which can potentially be improved with updated data and information. The model can also be used in combination with a modified version of Pak-IEM, to develop more realistic expansion plans, having significant shares of the renewable resources[9]. In addition, the research aided in highlighting the data gaps and ongoing efforts, regarding data collection in Pakistan.

1.4 Research Scope

The research area is interdisciplinary. It involved several disciplines and perspectives, including; environmental, ecological, social, planning, operational, etc. This research was carried out as part of a PhD, and it was essential to limit its scope. The research was, therefore, limited in order to assess the resource contributions and installed capacity as well as transmission system requirements, as mentioned before.

Furthermore, the grid system of Pakistan is expected to integrate with Central Asian countries, along with Afghanistan, through the Central Asia-South Asia (CASA) 1000 kV transmission line by 2020 (World Bank, 2015, p. 3). Similarly, there is a plan to increase the capacity of the existing 100 MW line, between Pakistan and Iran, to 1000 MW [10] (Reuter, 2015, p. [online]). Likewise, the possibility of an India and Pakistan grid integration systems also exists (Rahmand et al., 2011, p. 43). However, in this research, Pakistan's grid system was

[9] The concept is called hybrid modelling, and elaborated in the next chapter.
[10] Iran supply electricity to the border area of Pakistan through the existing 100 MW line.

considered in its' standalone mode. In the case of the mentioned developments, the system operational scenario will obviously change. Most probably, the scenario will aid a renewable electric system in the country, by having the option of power import and export.

1.5 Thesis Outline

This thesis consists of 12 chapters, including the introductory chapter 1. According to their contents, they are ordered as follows.

I. In chapter 02, there is an overview of the relevant research activities and approaches used. The chapter also discusses few well-known modelling frameworks from the perspective of this research. At the end, there are further details regarding the framing of the research questions.

II. The next chapter (i.e., 03) describes the analysis methodology of this research. This chapter consists of four sections, and each section describes a step of the calculations. The order of these sections is as follows: demand projection, demand-supply balance, transmission line requirements assessment, and total discounted system cost assessment.

III. In chapter 04, there are brief details about Pakistan, specifically, geographic, demographic, climate conditions, energy consumption, etc. This information can be helpful in reading the detail of the coming chapters, particularly of the renewable resources. Additionally, it has a brief discussion about the country's energy reserves and resources.

IV. Chapters 05, 06, 07, 08 of the thesis elaborate, in turn, the potential of the hydro, solar, wind and biomass resources in Pakistan. The chapters also discuss the current development status of the resources in the country.

V. Chapter 09 describes the demand forecasts of Pakistan, in two different economic growth scenarios, by 2050.

VI. In chapters 10 and 11, the findings of the research are presented. Chapter 10 presents the outcomes of the model (i.e., demand-supply balance simulations) at different temporal and spatial resolutions. While chapter 11 contains findings of the infrastructure requirements. This chapter also presents a techno-economic comparison of the supply cases (i.e., different combinations of the resources), considered in the research.

VII. The final chapter of the thesis presents a descriptive summary of, the findings and limitations of the work. It also contains a few recommendations for the implementation of the system.

Chapter 02: Literature Review and Research Questions

Recently, researchers have done significant work to assess the role of renewable resources in electricity and energy supply systems. The findings of which, assist in setting the resource targets for implementation and development. In this chapter a review of the efforts is presented, which helped in framing the theme of the research. The chapter also contains an overview of the modelling frameworks and tool, which are/can be used for the kind of research studies. Finally, the research questions are presented at the end of the chapter.

2.1 Renewable Energy System Assessment Studies

Generally, an analysis process is more complex while considering intermittent renewable resources in the supply mix of an energy system. The uncontrolled and site-specific generations of the resources forced the process to increase the detail level.

In Pakistan, the Planning Commission's (i.e., Pak-IEM) study is a well-known effort. As mentioned before, 15% share of the intermittent renewable resources was considered in a specific scenario (Planning Commission, 2010a, p. 22). However, the resources were dealt with at a basic detail level, considering a single region (i.e., country) and 12- time slices [11]. The deficiency of the lower spatial resolution is mentioned, and a transformation of the model from the country level to a regional level is suggested[12] (Planning Commission, 2010b, p. 13). Fortunately, there are studies analyzing renewable resources at a high detailed level. The studies were reviewed to assess their approach of analysis. In these studies, a few prominent in this field are briefly discussed.

— Sachverständigenrat für Umweltfragen[13] (SRU) (2011), Pathways Toward a 100% Renewable Electricity System: This is a detailed study, taken place under the auspices of the German Advisory Council on the Environment. The study analyzed the German power system in three different operational scenarios by 2050. In the first scenario (DE 100% SV), the system is assumed to operate in a standalone mode and utilize only the indigenous renewable resources. The second scenario (DE-DK-NO 85% SV) is based on a power exchange scenario with Danish and Norwegian systems. In the third scenario (DE-EUNA 85% SV), German power system exchanges the energy with the European countries and North Africa. In the last two scenarios, up to 15% net imports from the other power systems was permissible (SRU, 2011, p. 69).

[11] 12-time slices means i.e., (3-seasons/year, 1 type of day, and 4 periods of daily load variations. The concept is further elaborated in the upcoming sections of the chapter.

[12] The suggestion of spatial resolution increase is general one. However, in the presence of significant renewable resources, it is highly desired. The reason is explained in the later section of the chapter.

[13] German Advisory Council on the Environment

The study shows that around 160 GW capacity will be required for the German system to meet a demand of 509 TWh (by 2050). Similarly, the requirements are 250 GW in the high demand scenario (i.e., to meet 700 TWh). To reach the required capacity, wind and solar (i.e., PV) resources have to play a large role. The analysis also revealed the expansion and strengthening requirements of the transmission system. For example, 42 GW and 62 GW transmission capacity between Germany and Norway system will be required in the DE-DK-NO 85% SV scenario to handle the system operation in the two demand scenarios (SRU, 2011, pp. 117, 121, 137) respectively.

For the analysis at an hourly resolution, a modelling package was developed by the Institute of Engineering Thermodynamics, German Aerospace Center[14]. The package is called Renewable Energy Mix (REMix) (SRU, 2011, pp. 68-69,60). REMix is basically a combination of two models i.e., REMix EnDAT and REMix OptiMo (Figure 2. 1). As the figure shows, during an analysis, REMix EnDAT provides hourly resolution data of supply resources and demand. Using the inputs with additional information, REMix OptiMo solved the system to find a least cost supply system (i.e., resources) (DLR, 2013, p. [onlin])[15].

As the modelling environment and the scenarios suggest, the study is extremely detailed. Therefore, the work cannot be carried out by a single researcher. However, the study gave a general idea of analyzing a 100% renewable supply system.

— Mathiesen et al. (2015), Energy Vision 2050: A Smart Energy System Strategy for 100% Renewable Denmark: This is the latest contribution of the Danish Society of Engineers (i.e., IDA) to support the development of a 100% renewable energy system in Denmark. The analysis was done by the Department of Development and Planning, Aalborg University, Denmark. For analysis, EnergyPLAN was used to find hourly demand-supply balances in the years 2035 and 2050 (Mathiesen et al., 2015, pp. 45-46). EnergyPLAN is elaborated in the upcoming sections of the chapter.

The study compared the costs and benefits of a 100% renewable energy system with alternative options in Denmark. It assessed around 30 GW installed capacity requirements of the renewable supply options, mainly dominated by the wind resources, by 2050. The analysis

[14] In German, the name is "Deutsches Zentrum für Luft- und Raumfahrt (DLR)"

[15] REMix accessibility is limited, even cannot be purchased. This is confirmed through a telephonic conversation and email with DLR personnel (Dr. Christoph Schillings - Tel.: +49 711 6862-784 taken from: http://www.dlr.de/tt/desktopdefault.aspx/tabid-2904/4394_read-6500/) as the information were not found from other sources.

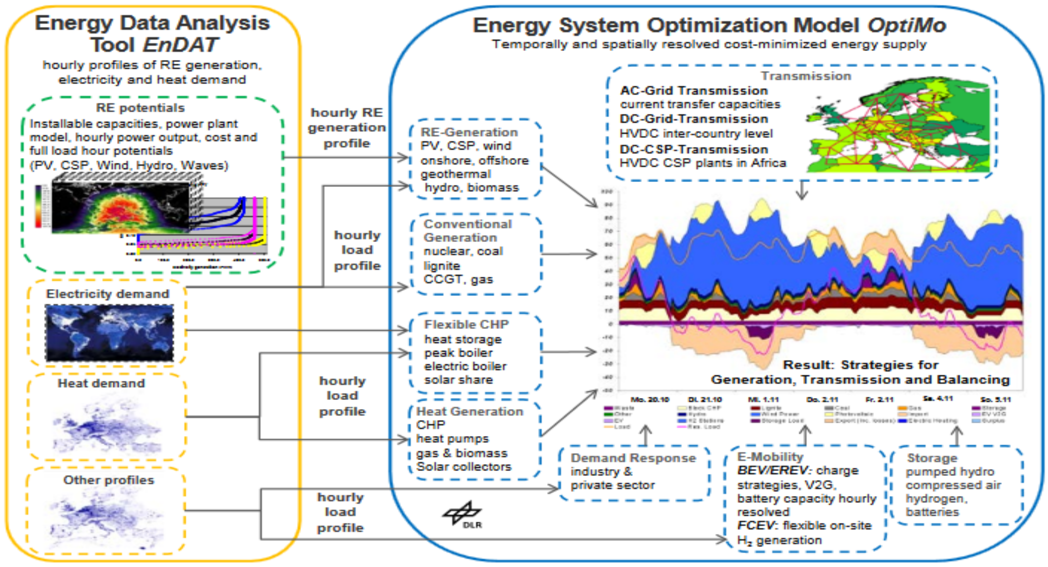


Figure 2. 1: REMix modelling environment and structure
Source: (DLR, 2013, p. [onlin])

also included an assessment of power flows across the border in a prospective energy market of the region (Mathiesen et al., 2015, pp. 16,19,43,66).

— Mathiesen et al. (2015b) and Østergaard et al. (2010)[16] are regional studies of the two Danish cities, Copenhagen and Aalborg, respectively. The studies analyzed the energy system of the two cities as an integral part of the country's system. In both studies, a renewable supply system was analyzed with an hourly temporal resolution, using EnergyPLAN. The objective of the work is to support the long-term planning and development efforts of a 100% renewable energy system in Denmark.

— Australia Energy Market Operator (AEMO) (2013), 100 Percent Renewables Study-Modelling Outcomes: Using the services of experts and consultants, the study has been executed by AEMO for its regional market (i.e., excluding west Australia and the Northern Regions[17]). The system is analyzed, considering two demand scenarios by 2050.

For the study, the system was modeled with an iterative approach and each iteration was completed in two steps (Figure 2. 2). In the first step, a probability-modelling tool was used to simulate 5000 random days. For each random day, the demand was fulfilled by the lowest cost supply option, consisted of the renewable resources and storage system. In the second step, a time-sequential model used the input capacities of the previous step. The sequential

[16] Online only available in Danish.
[17] The study is performed for Nation Electricity Market (NEM), Australia and cover around 20-30% area of the country.

model checked the capacity and the energy adequacy, with additional information of transmission system sufficiency/ requirements[18] (AEMO, 2013, p. 78), (Australian Govt - Departt. of the Environment, 2013, p. [online]). The analysis showed that the projected demand of 244 TWh and 318 TWh required capacities are 105 GW and 130 GW, respectively. In the total capacity, the majority of energy comes from the solar option (i.e., PV) (AEMO, 2013, pp. 14,27).

There are many similar studies that support this analysis, and the number is expected to grow. In Reedman (2012), one can find an overview of other studies that covered the topic of renewable resource based supply system analytics.

The studies, discussed earlier, are mostly executed by experts, who are given sufficient resources. As a part of a PhD research, it can be a challenge to initialize a study and achieve the needed detail level, particularly when compared to studies such as, (SRU, 2011), (Mathiesen et al., 2015) and (AEMO, 2013). The reason is understandable, as this type of research needs extensive data, diverse knowledge, programming and/or modelling skills, enough computational resources, etc. However, the overview was sufficient to get an idea of analyzing the demand-supply balance of Pakistan's electric power system, considering renewable resources.

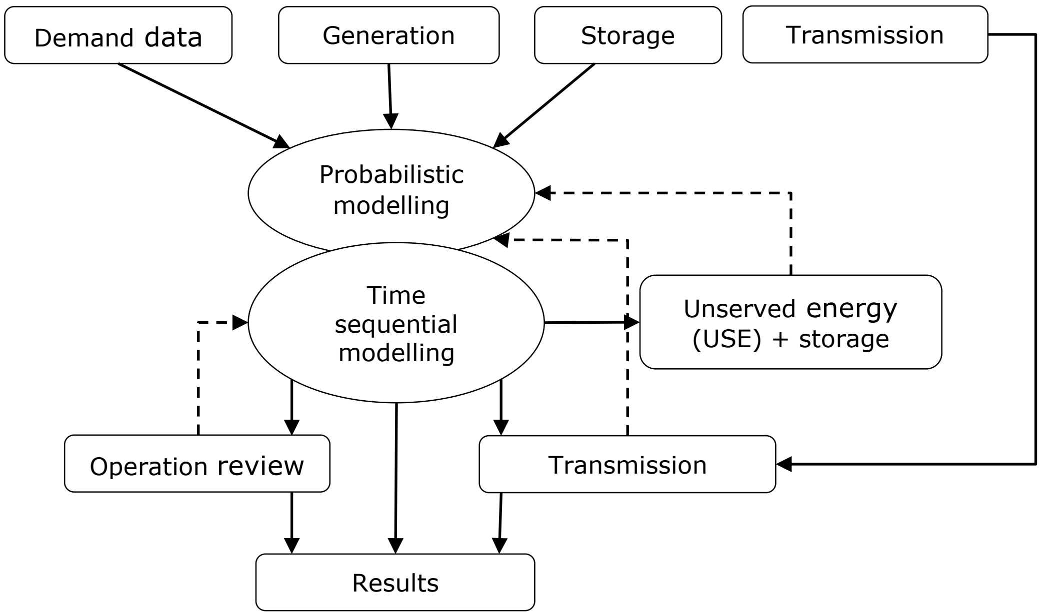


Figure 2. 2: Power system modelling approach used by AEMO 100% renewable study
Source: (AEMO, 2013, p. 78)

[18] No information were found regarding model nomenclature or availability and the study report describe only the approach.

2.2 Renewable Power Systems Planning and the Needs of Transmission System Infrastructure Assessment

Traditionally, expansion planning studies of electric supply system disregard the requirements of a transmission system[19]. The reason is understandable, as the approach is based on conventional resources. For most of the resources, the construction site is optimized according to load conditions and grid connection availability. In Basin Electric Power Cooperative (2008, pp. 11-12), there is a brief discussion regarding the site selection and evaluation of the Deer Creek Station (i.e., 300 MW). For the station, different sites were analyzed before selecting the final one. The discussion suggests that the general approach toward a transmission system expansion is reactive.

However, the reactive approach is not effective in the case of renewable resources due to their site-specific power generation[20]. According to Madrigal & Soft (2011, pp. 7,29), a proactive approach is more efficient and cost effective for a system possessing reasonable renewable resources. Following the same approach, in SRU (2011, pp. 66,93,155), the requirements of the transmission capacity for the anticipated renewable contribution were mentioned. The findings clearly revealed the requirements of the transmission lines not only across the border, but also within Germany. Similarly, in the AEMO (2013, pp. 20, 31-33), the transmission requirements are assessed by dividing the area under consideration into 43 regions for analysis.

2.3 Energy System Analysis and Modeling Frameworks/Tools

2.3.1 Classification Criteria

Energy systems are multi-dimensional in nature. For the decision-making process, a wide range of calculations is desired to assess the impacts of a policy. The revolution of computing technologies has aided in the development of frameworks for the purpose[21]. Using a framework, an analyst can conveniently model a system to find the solution. However, the diversity of the analysis objectives lead to the development of dozens of frameworks. In Connolly et al., (2010, pp. 1059-1082), an overview of well-known frameworks can be found. This diversity of the objectives makes it hard to classify the frameworks, based on a single criterion (Beek, 1999, S. 05). Nevertheless, the major criterion for influencing the development of an energy modelling framework will now be discussed.

[19] The exception could be studies considering more than one system (i.e., countries), the requirements are considered, to assess the infrastructure requirements.

[20] The only exception can be biomass based generation.

[21] The word "framework" is used in a general sense to represent both the frameworks and tools. However, later in the chapter, the two are differentiated.

2.3.1.1 Modelling Approach

There are basically two major modelling approaches that involve the incorporation of energy system dynamics.

These approaches are top-down and bottom-up. The top-down models are also referred to as macroeconomic models due to their use of macroeconomic parameters (i.e., energy, labor, capital, etc.) and energy prices in the decision process (SRU, 2011, p. 34). An example of a well-known top-down model is ENPEP (*Energy and Power Evaluation Program*) (Connolly et al., 2010, p. 1063).

On the other hand, the bottom-up approach incorporates the engineering aspects of the technologies. It also includes the development of these technologies, focusing on efficiency improvements, and the market penetration of new technologies, etc., (SRU, 2011, p. 34). Generally, the frameworks needed to define an energy system for analyzing different policies, must be very precise and detailed. The examples of such frameworks are; TIMES (*The Integrated MARKAL-EFOM System)*[22] and MESSAGE (*Model for Energy Supply Strategy Alternatives and their General Environmental Impacts)* (Connolly et al., 2010, p. 1063).

2.3.1.2 Optimization vs Accounting/Simulation Models

Optimization models are used to select the cheapest mix of power generation technologies under specified constraints. MESSAGE, TIMES, and WASP[23] (Wien Automatic Strategy Plans), are good examples of the investment optimization's frameworks (Connolly et al., 2010, p. 1063).

On the other hand, an accounting framework assigns available energy resources to meet the demand. Generally, a supply mix found by using the type of model depends upon the user's approach and skills. An example of such tool can be LEAP (Long-range Energy Alternatives Planning System)[24] (Connolly et al., 2010, p. 1063).

2.3.1.3 Temporal Resolution and Modelling Time Horizon

Long and medium term expansion planning needs analysis of the demand-supply system across several years or even decades, and a model is needed that spans that period. The frameworks like TIMES and MESSAGE can be used for this kind of analysis, but they are limited or preferred to be used in low temporal resolution cases. According to Connolly (2010, p. 1064), TIMES can be used for hourly simulation. However, Pina (2013, pp. 215-223)

[22] TIMES incorporated the demand elasticity in regards of price change, therefore, it is sometime referred as hybrid of the two approaches.
[23] WASP has almost no option of constraints. It is user capability to do so, through inputs.
[24] Recently, LEAP has been combined with OsyMOSE for optimization, however, both of them maintained their identity, therefore, it is difficult to call the new package of LEAP as optimization one.

discourages the use due to associated complexities of calculations and system modelling[25]. Generally, these frameworks handle the variations in demand by dividing a year into a limited number of time slices[26]. The frameworks are, therefore, discouraged for a system having a substantial share of intermittent renewable resources, without the support of a high temporal resolution modelling tool.

On the other hand, the renewable energy system dedicated frameworks like HOMER (Hybrid Optimization of Multiple Energy Resources), RENPAS (Renewable Pathways Simulation System)[27], and EnergyPLAN use a high temporal resolution, but the time horizon of modelling is only one year (Connolly et al., 2010, p. 1064), (Wiese, 2014, p. 11). The models generally highlight the operational aspects of a renewable supply system, by finding an hourly demand-supply balance across a year, focusing on the lowest cost possible.

2.3.1.4 Spatial Resolution

Spatial resolution becomes important when the covered area of a system under consideration is big enough. To evaluate the flows of material, energy, and power among different regions, some frameworks use the concept of multi–regions. TIMES and MESSAGE are examples of this kind of framework. On the other hand, frameworks like EnergyPLAN and HOMER consider the system area as a single region (i.e., point) (Connolly et al., 2010, p. 1064). Therefore, these modelling tools are more suitable for the analysis of a single region or a micro grid.

The growing research in the area of renewable energy system, helped in the development of modelling packages, with both high temporal and spatial resolution (e.g., REMix). Generally, the package consists of more than one modelling tool. However, they are mostly developed for a specific case study and/or limited to be accessed.

2.3.2 Energy/Power System Modeling Frameworks Review

Development of an energy modelling framework is a continuous process, and most of them evolve and improve over time. Furthermore, the community is substantially big and growing (Beek, 1999, p. 05). According to Connolly et al., (2010, p. 1065), there were more than 50 modelling tools and frameworks by 2009-10. It is, therefore, beyond the scope of this research to explore and describe all of them. Still, while looking for a suitable one, few well-known[28] frameworks were reviewed in the research.

[25] The complexity is briefly discussed in the next section.
[26] The concept is further elaborated in the later section.
[27] RENPAS also permit simulation at an interval of quarter part of hour (i.e., 15 min)
[28] Here, use of the word "well-known models" is relative ,and due to a large number of the modelling tool, it can be different for another person.

The review was specifically in the context of the research objectives and done from a user perspective. Based on the review, the frameworks are classified into the following three broader categories.

2.3.2.1 Expansion Planning Frameworks

2.3.2.1.1 Demand-Supply Systems Handling Approach

Generally, the development of these frameworks was initiated during the 1980s. Therefore, their approach is more suitable while considering a conventional energy system[29]. They are generally available in sophisticated computer packages (e.g., MARKAL/TIMES, MESSAGE, LEAP etc.). The frameworks are quite flexible in their use for modelling an energy system. They provide an opportunity to define a system fully or partially (e.g., only power system) by using the concept of a reference energy system (RES) (Figure 2. 3). RES is basically a layout of nodes and links, where nodes represent technologies, source, etc., while links energy commodities and carriers, etc., (Loulou et al., 2004, p. 12). Consequently, there is no limit on the commodities or technologies definition to model a system. In the example of the figure, different level of technologies and commodities can be seen, in a base year and across the modelling horizon.

To model a system, these frameworks generally consider the following five forms of energy commodities/carriers (Nakicenovic & Riahi, 2003, p. 7) (IIASA, 2013, p. [online]);

- **Resource** means the form of energy, yet to be extracted or mined (e.g., oil and coal reserves).
- **Primary Energy** represents the tapped and available energy resources (e.g., crude oil at a refinery).
- **Secondary Energy** means the energy carrier at its generation point (e.g., diesel produced in refinery, electricity at power plant. etc.).
- **Final Energy** is the energy forms (i.e., carrier) which can be accessed/used by a consumer (e.g., electricity at home, gasoline in car tank, etc.).
- **Useful Energy** is the part of supplied energy, which satisfy the demand of an end-use service (e.g., lighting, heating, cooking, etc.).

[29] Based on oil, coal, nuclear, hydro, etc.,

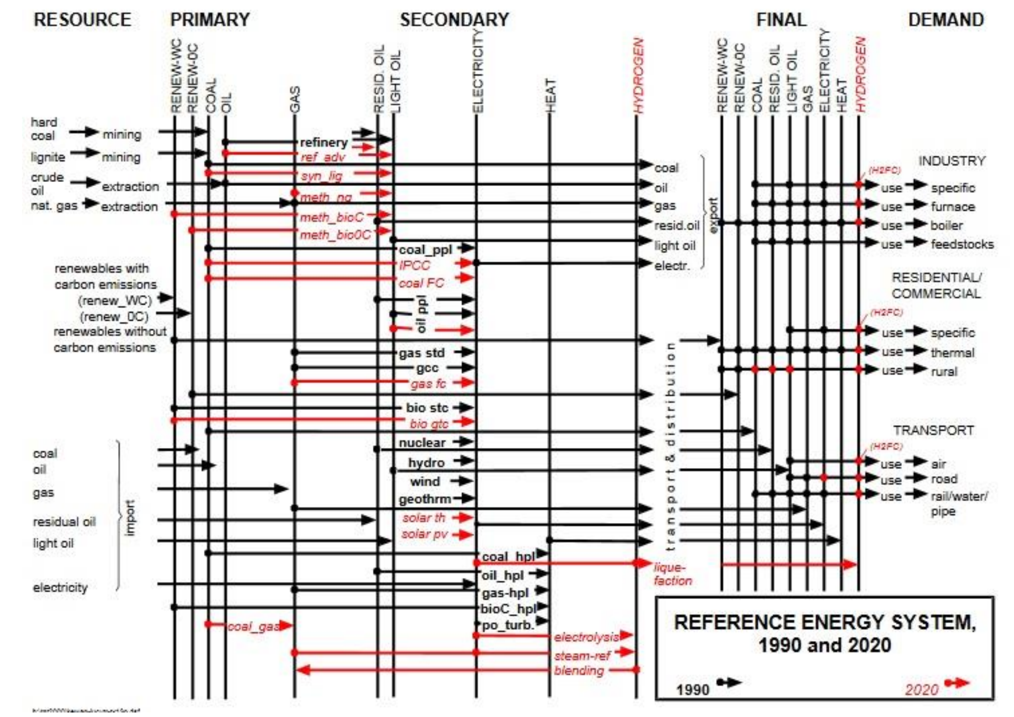


Figure 2. 3: General layout of a typical RES (i.e., of MESSAGE), with prospective supply options
Source: (Nakicenovic & Riahi, 2003, p. 7)

2.3.2.1.2 System Modelling

While using the type of frameworks, a user defines the number of regions, modelling horizon, number of periods in the horizon and an approximation of the system chronological load demand curve (LDC). The approximation means that LDC is generated by dividing a year into seasons, a season in type of days per week and a day in different time slots (according to demand condition). For further clarification, Figure 2. 4 graphically presents the definition of a system's LDC. The sample consists of four seasons, two types of days per week in each season, and two distinct periods per day in each type of day (Loulou et al., 2005, p. 12).

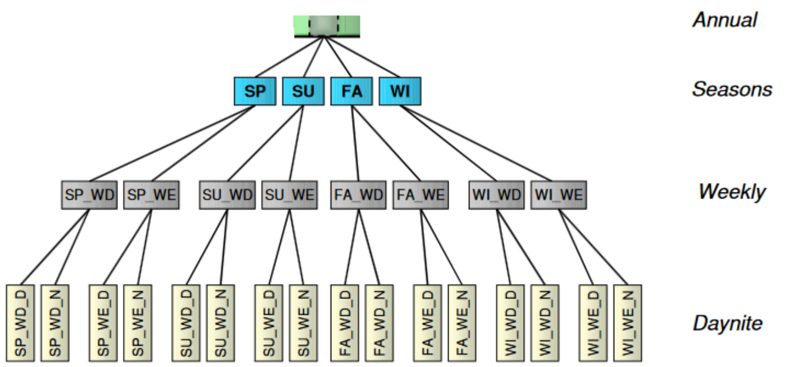
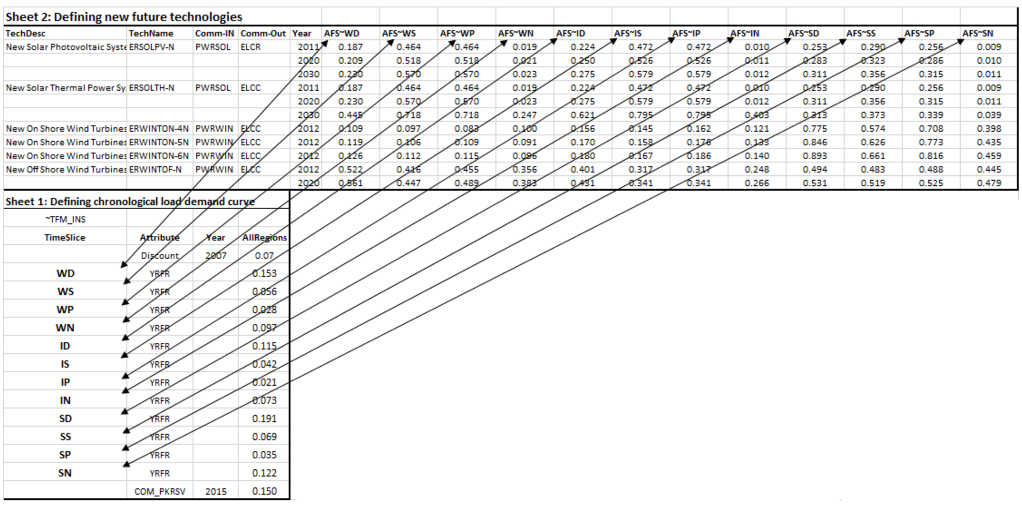


Figure 2. 4: A sample of representing the chronological LDC
Source: (Loulou et al., 2005, p. 12)

Commonly, the definition of the LDC is limited either by the framework built-in properties (e.g., there is a limit of 64 time slices in MESSAGE while only 06 in MARKAL[30]) (IAEA, 2003, p. 3(5)); (Loulou et al., 2004, p. 11), or associated complexities with the addition of time slices.

The associated modelling complexity with an increase in time slices (i.e., temporal resolution) is explained with the help of Figure 2. 5. The figure presents two (i.e., merged) templates of Pak-IEM (i.e., developed in TIMES). In the one, 12-time slices are defined to approximate the LDC of Pakistan. In the second template, the slices are referred to describe the availability of wind and PV resources. From this, it can be easily concluded that it is the user's responsibility to refer the slices in the model (i.e., for demand and resources)[31]. Commonly, to handle the issue of a low temporal resolution, a hybrid modelling approach is adopted for an analysis i.e., using the framework in combination with another high temporal resolution tools or framework. The approach is discussed later in the section, as a separate category.

Next, to model the system, users need to provide the information of demand[32], energy resources, existing and prospective technology options, fixed and operational cost, technologies service life, existing capacity, developing/construction period, new technologies, etc. Similarly, different policies can be analyzed by defining a wide range of constraints/limits on commodities and technologies, including, resources, capacity installation, investment, GHG emissions, market penetration, etc., (IAEA, 2003, pp. [1-1])



Sheet 2: Defining new future technologies

TechDesc	TechName	Comm-IN	Comm-Out	Year	AFS~WD	AFS~WS	AFS~WP	AFS~WN	AFS~ID	AFS~IS	AFS~IP	AFS~IN	AFS~SD	AFS~SS	AFS~SP	AFS~SN
New Solar Photovoltaic Syste	ERSOLPV-N	PWRSOL	ELCR	2011	0.187	0.464	0.464	0.019	0.224	0.472	0.472	0.010	0.253	0.290	0.256	0.009
				2020	0.209	0.518	0.518	0.021	0.250	0.526	0.526	0.011	0.283	0.323	0.286	0.010
				2030	0.230	0.570	0.570	0.023	0.275	0.579	0.579	0.012	0.311	0.356	0.315	0.011
New Solar Thermal Power Sy	ERSOLTH-N	PWRSOL	ELCC	2011	0.187	0.464	0.464	0.019	0.224	0.472	0.472	0.010	0.253	0.290	0.256	0.009
				2020	0.230	0.570	0.570	0.023	0.275	0.579	0.579	0.012	0.311	0.356	0.315	0.011
				2030	0.445	0.718	0.718	0.247	0.621	0.795	0.795	0.403	0.313	0.373	0.339	0.039
New On Shore Wind Turbines	ERWINTON-4N	PWRWIN	ELCC	2012	0.109	0.097	0.083	0.100	0.156	0.145	0.162	0.121	0.775	0.574	0.708	0.398
New On Shore Wind Turbines	ERWINTON-5N	PWRWIN	ELCC	2012	0.119	0.106	0.109	0.091	0.170	0.158	0.176	0.133	0.846	0.626	0.773	0.435
New On Shore Wind Turbines	ERWINTON-6N	PWRWIN	ELCC	2012	0.126	0.112	0.115	0.096	0.180	0.167	0.186	0.140	0.893	0.661	0.816	0.459
New Off Shore Wind Turbines	ERWINTOF-N	PWRWIN	ELCC	2012	0.522	0.416	0.455	0.356	0.401	0.317	0.317	0.248	0.494	0.483	0.488	0.445
				2020	0.561	0.447	0.489	0.383	0.431	0.341	0.341	0.266	0.531	0.519	0.525	0.479

Sheet 1: Defining chronological load demand curve

~TFM_INS			
TimeSlice	Attribute	Year	AllRegions
	Discount	2007	0.07
WD	YRFR		0.153
WS	YRFR		0.056
WP	YRFR		0.028
WN	YRFR		0.097
ID	YRFR		0.115
IS	YRFR		0.042
IP	YRFR		0.021
IN	YRFR		0.073
SD	YRFR		0.191
SS	YRFR		0.069
SP	YRFR		0.035
SN	YRFR		0.122
	COM_PKRSV	2015	0.150

Figure 2. 5: Chronological LDC and its use to model intermittent renewable (wind, solar) resources in Pak-IEM- The figure consisted of Pak-IEM two templates and taken directly from the model. However, a description of the LDC in the figure can be found in Planning Commission (2010, pp. 15-18)

[30] TIMES is the latest and upgraded form of MARKAL. In TIMES, there is no such limit

[31] The associated increase in the computational process is discussed later in the section.

[32] The definition of demand side can be different from one framework to other. For example, MESSAGE takes the system total final demand, while TIMES gives the opportunity to define the side up to end-use services.

The frameworks do not have dedicated features to handle renewable resources specific characteristics. It is, therefore, the user's responsibility to calculate their generations and provide the capacity factors and availability factors at the defined temporal resolution. Furthermore, the user will need to assess the changes in the capacity factors, while considering a substantial share of intermittent renewable resources.

2.3.2.1.3 System Solution

In general, to find a solution, two different approaches can be found in the type of frameworks i.e., optimization and accounting.

Optimization frameworks (e.g., TIMES, MESSAGE) use the techniques of linear and mix integer programming to find a solution. In the computer package of the frameworks, there is always a matrix (i.e., linear equations) generator and a mathematical solver[33]. The generator produces linear equations in a specified format, using the input information. The solver produces a least cost solution by solving the system (i.e., equations). To understand the technique of solving the system, sufficient knowledge of operational research (linear programming) is required. It is beyond the scope of the work to discuss the techniques, therefore, only the objective function of MESSAGE framework is presented in a descriptive form. A detailed equation of which can be found in the framework manual (IAEA, 2003, pp. 37-38).

$$Objective\ Function = \sum_{Period=1}^{n} \left(Discounted \begin{pmatrix} Investment\ Cost(i), \\ Operation\ cost(i), \\ Demand\ elasticity\ cost\ (i), etc., \end{pmatrix} \right)$$

In the previous section, the time slice limitations were discussed from a modeller's perspective. However, the increase of the slices (temporal resolution) also increases the computational burden and storage requirements. With an increase in the time slices, the matrix size (i.e., equations) increases linearly, while the computational time almost exponentially increases to find a solution (Giannakidis et al., 2015, pp. 190-197). This can be hard for some users to accommodate. Finally, after finding an optimal solution, the frameworks report different parameters, including, installed capacity requirement, generation mix, system discounted cost, emissions, etc.

On the other hand, the accounting frameworks (e.g., LEAP) uses a simple calculation approach to find a demand-supply balance. Therefore, the solution is not necessarily an optimal one. The reason is that, as the shares of the supply resources are decided during the

[33] Solver are available both as commercial package and open access. Generally, the commercial (e.g., CPLEX) are relatively faster to find a solution of a given linear equations.

model/scenario developments transpire. Generally, a user defines several scenarios, in order to compare their findings. This helps to assess the impact of a certain policy. The main advantage of using the frameworks is their calculation simplicity and transparency (Heaps, 2002, pp. [slide-9]).

2.3.2.2 Renewable Energy Supply System Modelling Tools[34]

In the recent past, few dedicated modelling tools have been developed to model a 100% renewable energy or a hybrid supply system. The frameworks use an hourly temporal resolution to incorporate the operational aspects of the system. However, their spatial resolution is limited to a single region, and the modelling time horizon is one year. This means that the tools do not solve a system for a medium or long-term expansion planning. In this category, the well-known modelling tools are EnergyPLAN and HOMER. Since the development philosophy of the two tools is different, therefore, their review is presented in two different sections. Additionally, a framework has been developed by the NREL, which has a high temporal resolution, and is also briefly discussed at the end of the section.

2.3.2.2.1 EnergyPLAN[35]

The EnergyPLAN modelling tool was developed to analyze supply systems, mainly based on renewable energy resources. However, the tool is open to considering fossil fuels for some uses e.g., individual house heating system can use coal, oil, natural gas and biomass to meet the demand. Similarly, nuclear power generation[36] and electric power import/export options can also be used to model a system. The definition of an energy system in the tools used for modelling is fixed, but also a detailed one. The demands of electricity, heat, and fuel are demarcated by different sub-systems. Similarly, a supply side can be part of a model by considering electricity and heat generations of renewable resources, CHP plants, nuclear power generation, storage systems, etc. (Lund, 2013, pp. 12-16). This concept makes the tool flexible and able to be adapted for modeling different systems.

The concept of the EnergyPLAN modelling tool is to analyze a well-coordinated energy system, in which the use of electricity and heat are divided into fixed and flexible components. The electricity generation of different control and uncontrolled options are used to meet the demand (Figure 2. 6). To handle the operation (i.e., system simulation), utilization priorities are defined internally under two different regulation conditions; I) technical and II) market-

[34] It is noteworthy that instead of framework, word "tool" has been used. This is done intentionally to reflect the adaptability limitation of the two models.
[35] EnergyPLAN is available free of cost
[36] The option is named as nuclear power in the instruction of the model, however, it can be any controlled generator and the model will deal it as base-load supply.

economics. A user can opt for one of the two conditions, as per analysis requirements (Lund, 2013, pp. 9, 12-17).

Briefly, in the case of technical regulation, the demand of electricity and/or heat is fulfilled without considering (external) market prices. In the second case, the market prices affect the operation of different electrical power generation systems. However, under both conditions, the import and export are within a predefined limit. Beside the internal control of the energy carrier flow and system operation, the tool allows its user to control some calculations. For example, the user can prioritize supply options to be reduced. During simulation, the priorities are considered when generations exceed the demand (Lund, 2013, pp. 81-84, 89).

To model a system, the critical data requirements are annual value and/or hourly distribution of the following (Lund, 2013, pp. 29-50);

- Sub-system(s) electricity and heat demands,
- Renewable (wind, PV, solar thermal, wave) power generation,
- Nuclear power generation,
- Different type CHP generation,
- Hydropower generation,
- Reversible generation (e.g., pump storage)
- Water inflow in reservoir/storage,
- Waste usage in different sub-system,
- External market prices, etc.,

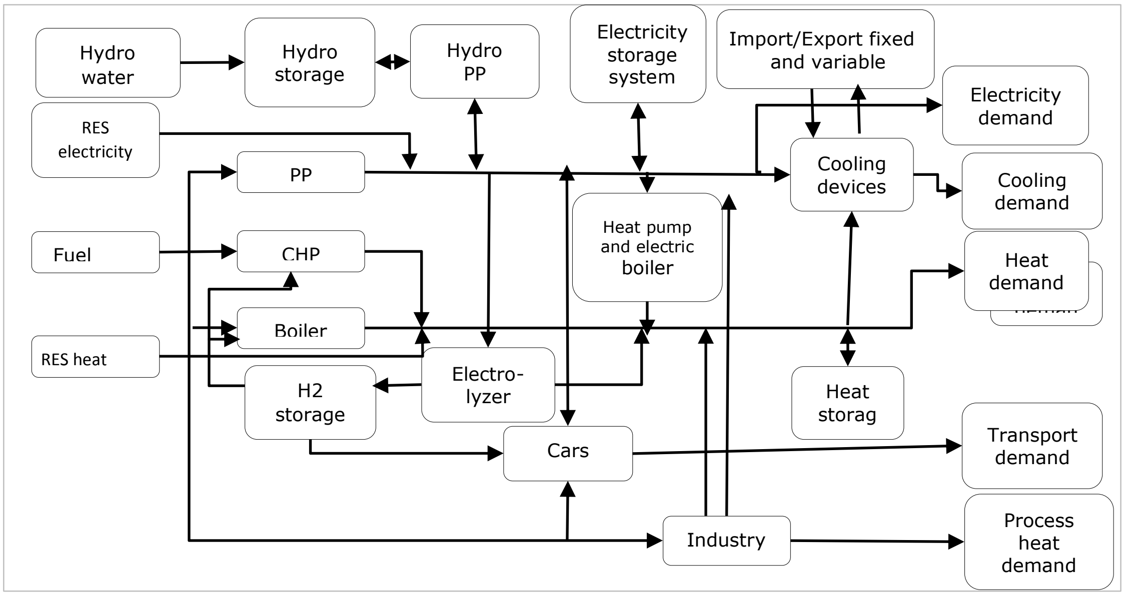


Figure 2. 6: A layout of energy system definition in EnergyPLAN
Source: (Lund, 2013, p. 39)

In the tool, there is a single representation of each demand sub-system and supply option. It is, therefore, the user's responsibility to ensure that the distribution profiles are representative of the energy system. For reservoir operation, the tool distributes total water inflows differently under the two-optimization conditions. In the technical optimization, the stored energy is used to avoid excess generations. While in the market-economic case, profit maximization is the criteria for reservoir operation (Lund, 2013, p. 12).

While reviewing EnergyPLAN, some limitations were observed regarding the tool use for this research (i.e., to analyze a renewable electric supply system in Pakistan). These limitations are briefly discussed below.

- Since the tool uses a single region concept, therefore, its use is limited if an energy/power system consists of multiple region. Commonly, the concept of multiple regions is adopted to assess the inter-regional flows. The flows indicates the inter-regional dependency and can be used to estimate transmission line requirements. Obviously, this kind of analysis is useful in the long-term planning for future implementation of the system.
- The second limitation was observed in the handling of hydropower generation. The tool handles the river generation (i.e., run of river hydro power plant (RORHPP)) and hydro storage (reservoir based hydropower plant (RHPP)) independent of one another. For RORHPP[37], the tool uses total annual generation and its hourly distribution. On the other hand, RHPP generations are optimized either to meet the demand with least capacity or maximize profit. The concept is unlikely to be used under the following conditions[38].
  - If an RHPP discharge affects power generation of downstream RORHPPs[39], a new distribution profile of RORHPP generation will develop. This means that the profile used in the model has to be updated. However, with the new updated profile, there is a high probability that the tool optimizes the stored energy (i.e., RHPP generation) in a different way.
  - If there are more than one reservoir along a river (in the cascading position), it is hard to find/prepare a single distribution profile of water inflow and a representative total storage capacity. Because, in this case, the inflow of downstream reservoirs depend on the release of one upstream. This makes the situation a complex one to model.
  - If downstream water requirements are more important than generation optimization, it is unlikely to have a multi-purpose optimal water discharge.

[37] From the tool perspective, RORHPP means any hydropower generation, which use the user input distribution across a year.
[38] Confirmed from the developer/in charge of the tool through email.
[39] For example, in Pakistan, Ghazi-Barotha RORHPP (1450 MW) intake is at the discharge point of the Tarbela RHPP. Further details can be found in the "Hydro Resources" chapter of the thesis.

In the three situations above, a compromised solution is as follows; to simulate the hydro system (RORHPP+RHPP) outside EnergyPLAN [40] and prepare a distribution profile of hydro generations. Then to use the profile with total hydropower capacity as RORHPP in the model, while ignoring the reservoir potential.

2.3.2.2.2 HOMER[41]

HOMER is originally developed to analyze a micro-power generation system, in a standalone or grid connected mode. Like EnergyPLAN, HOMER also analyzes the operational aspects of a system and covers a time horizon of one year. The tool provides an opportunity to define a system, considering up to (Figure 2. 7) (HOMER, [n.d], p. [Help]);

- 10-types of each diesel generators and batteries,
- 02-types of wind turbine,
- 01-type of each PV and RORHPP,
- 02-types of each primary load (electricity demand) and thermal loads,
- 01-type of each deferrable load and hydrogen load with its electrolyzer, storage tank, and reformer.

For each type of component (e.g., wind turbines), one can define a different number of units/capacities. Furthermore, each component requires relevant information, particularly, performance parameters and cost data. HOMER demonstrates the different options available, including diesel generators and batteries, which are needed in the various micro-grid systems.

For modelling a system, HOMER required a high temporal resolution data of demand and supply resources. In the tool, there are two options to handle/prepare the data. First, if hourly data are available, they can be imported conveniently (i.e., from a text file). In the second case, a user needs to provide monthly means data (i.e., of demand, wind speed, solar insolation etc.,).The tool synthetically generates hourly values from them.

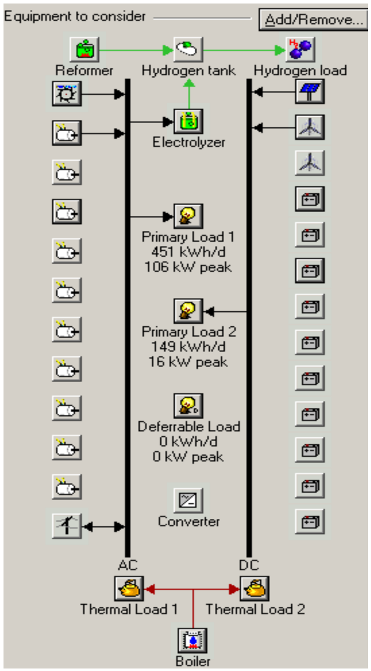


Figure 2. 7: HOMER's layout to define an energy system (The figure is generate by the author from the HOMER 2.68 beta version)

[40] This will need an additional modelling tool, or can do through calculation i.e., in MS Excel
[41] It is a commercial modelling tool and the review is based upon HOMER 2.68 beta version.

A third option is also available, but only for wind speed and solar insolation data. This option can be used by providing the location of the micro-grid/project, and the tool imports the data from online sources[42] (HOMER, [n.d], p. [Help]). Using the input data and information, HOMER finds different cases of technically feasible supply combinations and ranks them according to their total cost (i.e., NPV) (Farret & Simões, 2006, p. 385). The NPV is based upon investment cost, O&M cost, fixed cost, salvage value etc. HOMER is a suitable option for analyzing the operational feasibility of a micro-grid system. Therefore, the tool is limited in the case of multiple regions. Furthermore, it has no option of defining the RHPP or a river system.

2.3.2.2.3 ReEDS and RPM

NREL has developed the ReEDS (Regional Energy Deployment System) for the USA power system. The model temporal resolution consisted of 17 time slices[43], with enough spatial resolution. The objective of the model was to assess the renewable resources spatial variation and transmission system requirements (Short et al., 2011, pp. 6-8). Later, the experience was used in the development of RPM (Resource Planning Model). RPM is a modelling tool, using an hourly resolution with the option of defining regions. The time horizon of the tool is one year and can be used for the analysis of an electricity market. According to the NREL, Colorado's electric system has been modeled using RPM. However, the information (i.e., terms and conditions) regarding its availability is not given (NREL, [n.d], p. [online]).

There are some tools, which are developed as a model for a specific region. The tools are, therefore, hard to be adapted. For example, RENPASS has a layout, containing a model of Germany and 15 other European countries (Wiese, 2014, p. 11).

2.3.2.3 Hybrid Modelling Approach (HMA)

HMA is actually an approach of modelling, rather than a category of the modelling frameworks. The approach is general adopted when dealing with the expansion planning of a system that has reasonable intermittent resources.

In HMA, a high temporal resolution tool is used to incorporate operational aspects of the supply system. The results of which are used in a low resolution framework, for finding a long term expansion plan. A well-known application of the approach is in the package developed by the Institute for Industrial Production, Universität Karlsruhe, Germany (Figure 2. 8). The institute has coupled optimization framework PERSEUS-CERT (Programme-package for

[42] User must be connected to the internet while using the option.

[43] The temporal resolution consisted of 4 seasons and 4 daily variations per day in each season. One additional slice per day is added to the summer for assessing the system peak.

Emission Reduction Strategies in Energy Use and Supply-Certificate Trading) with the AEOLIUS (Rosen et al., 2007, pp. 575-583).

PERSEUS-CERT has been used to model the energy system of 21 European countries, represented by 25-region. The model uses the system optimization approach to generate an expansion plan under specified constraints. Its modelling time horizon limit is 50-years, with time slices of 36-72 per year. On the other hand, AEOLIUS is a power plant dispatch-modelling tool, using a temporal resolution of 15-minutes. Both, the framework and the tool use the outputs of one another to analyze different scenarios (Rosen et al., 2007, pp. 575-583) (EnergyPLAN, 2016, p. [online]). It is important to mention that AEOLIUS is available only to the stakeholder for a specific use, while PERSEUS-CERT was sold to a number of energy utilities. Therefore, access to the package is limited (EnergyPLAN, 2016, p. [online]).

A similar approach can be found in Pina et al., (2013). In the research, a combination of EnergyPLAN and TIMES is used, to model and analyze the energy supply system of Mainland Portugal. For modelling, 288-time slices (temporal resolution) are defined in TIMES. The general objective of the work is to assess the impact of renewable resources penetration on the system.

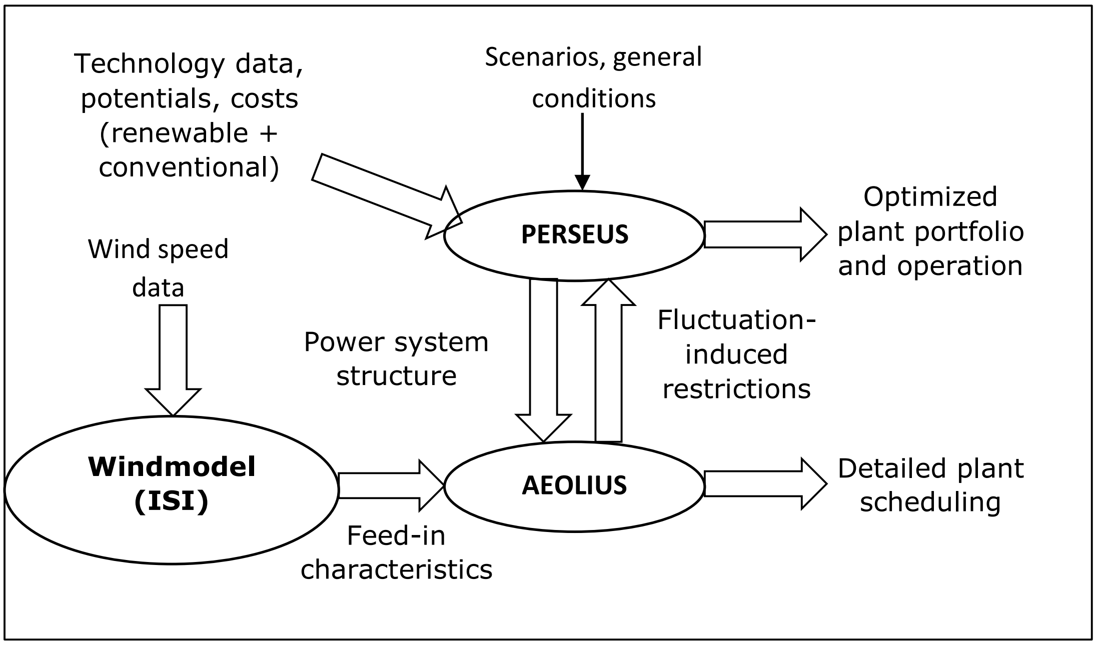


Figure 2. 8: A modelling and working environment of PERSEUS-CERT and Aeolius
Source: (Rosen et al., 2007, p. 577)

2.4 Research Theme and Questions

From review, it was assessed that the resources requirements are substantially high for analyses of an energy system, considering renewable supply resources. The reason is obviously a high temporal resolution of the demand-supply balance. Therefore, as mentioned before, the research was limited to consider only the electric power system of Pakistan.

Pakistan is a big and highly diversified country. Due to its size, and to previously mentioned points, a high spatial resolution was desired[44]. However, the review also revealed the limitation of a modelling framework/tool availability/use. The limitations were obvious; low resolutions and/or suitability and accessibility of the frameworks. Consequently, the work was carried out by developing and using a time-sequential model for the system. Later, the results of the balance were manipulated and used in MESSAGE for a techno-economic comparison of the cases. The analytical work was thus focused on finding and assessing the answer of the following research questions.

I. Can Pakistan fulfill the electricity requirements from indigenous renewable resources by 2050, under different demand and supply conditions? The question specifically covered the technical feasibility aspects of the system operation and finding the contribution of the available renewable supply options.
II. What will be the prospective capacity requirements of the resources to develop the system? The question is closely related to the first one. However, the answer of this question provides more details. For example, the total requirement (TWh) of the biomass resource was covered by the first question, while the installed capacity (GW) by the second one.
III. What will be the regional-dependency situation be like within the country? The research work in the context helped to identify the critical regions. The findings can help in the implementation of the system. For example, the distribution of biomass generation capacity, or the investigation and implementation of storage options is relevant here.
IV. What will be the estimated-requirements of the transmission system to operate the system? The question is added to the research in order to estimate the system's overall infrastructure requirements.
V. Which resource mix (i.e., supply case) can be more economical for the development of the system by 2050? The only objective of this research part was to compare the different supply combinations (i.e., cases)

[44] More details about spatial resolution and covered area are given in the next two chapters of the thesis.

2.5 Chapter Summary

Renewable electric and energy systems are being considered among the possible solutions to deal with the Climate Change issue. This research is carried out to assess a renewable electric supply system in Pakistan. The ultimate objective of which is to support the resources development in Pakistan and to help in setting the long-term targets of the resources for the future energy plans of the country. However, the work is limited to find only the infrastructure requirements and contribution of the resources, in fulfilling demand.

To investigate a system covering such a big area as Pakistan, a high spatial resolution was desired for the analysis. In the recent past, several models were developed with hourly temporal resolution and enough spatial resolution. However, most of them are study (i.e., system) specific, and/or too limited to be adopted or accessed. Consequently, a simulation framework has been developed and used for the demand-supply balance analysis of the system. The output of which were manipulated to find an economical combination of the resources, using the MESSAGE model.

Chapter 03: Analysis Methodology and Approach

In this research, an analysis of the electricity supply system was the most important task. To accomplish the task, a simulation of the demand-supply balance in the year 2050 was mandatory. It means that besides the data of the supply resources, a forecasted value of the demand by 2050 was also required. Furthermore, calculations were also performed, for an assessment of the transmission lines requirements and finding an economical supply combination of the resources.

In the following sections, the approaches used for different tasks are explained. The first section discusses the approach of the demand forecasting. Following this, the next section describes the methodology used for the demand-supply balance. Regarding transmission lines assessment, the findings of the demand-supply balances were used with lines' load-ability. For load-ability and thermal loss calculation, a method available in the literature of the electric power engineering was used. Details of which can be found in the third section of the chapter. Finally, the results of the three modules were manipulated and used in the MESSAGE framework, to find an economical combination of the supply resources. The work also needed calculations for the assessment of the supply resources, but they are discussed in the relevant chapters.

3.1 Demand Forecasting

According to Bhattacharya & Timilsina (2009, p. 17), the research work of the past in the area of demand forecast resulted in two major approaches, i.e., "econometric" and "end use". The econometric approach based on economic theories and rules, to develop a forecasting model. The model is then validated by using historical data. Which means that a developed model by the approach is applicable for a specific system.

The second approach uses the techniques of coherent accounting. With slight variations in the layout, the general form of the approach is available in several frameworks, including; MAED[45] (Model for Analysis of Energy Demand), LEAP and TIMES[46], etc. In this research, the "end-use" approach is used at a brief (i.e., sectoral) level and only for a forecast of the electricity demand. However, for information, a summary of the approach is presented in the following section. The summary can help to know the significance of the assumptions, taken in this particular research case.

[45] MAED is specifically developed only for demand forecast of the energy system.
[46] TIMES deal both demand and supply side (i.e., in the same model).

3.1.1 End-Use Approach

The first step of the approach is to identify the sectors of an energy system. In general, they are: residential, commercial, transport, agriculture, industry, mining, construction, livestock, fisheries, etc. Due to the variation in size of the sectors from country to country, a small one can be considered as a sub-sector of a major one. For example, in MAED, the system is divided into three main sectors i.e., economic, residential and transport. Additionally, the economic sector has six sub-sectors in the defined layout of the tool. These sub-sectors are commercial, agriculture, manufacturing, mining, construction, energy. However, except energy, the four can be split, up to 10 constituents (IAEA, 2006, p. 09).

3.1.1.1 Detail Levels

Base-Year Sectoral Consumptions:

The first level required for the demand forecast is the base-year energy consumptions of the sectors. Generally, at the level, data are provided in an absolute form. In the sub-levels (i.e., more detailed ones), values of different parameters, including, activity, intensities, etc., are brought into line to maintain a balance of the base-year consumption (Stockholm Environment Institute (SEI), 2005, p. 91). In most cases, governments and international agencies regularly publish the information. In the case of information being unavailable, the consumptions are approximated, maintaining the following condition.

$$Total\ enregy\ consumption = \sum_{i=1}^{s}(Energy\ consumption)^{i}$$ … … … …*eq. 3. 1*

$Where\ the\ system\ consisted\ of\ s - number\ of\ sectors$

Energy Carriers:

Energy is consumed by a system in many forms, called energy carriers. The mix of the carriers can vary among sectors and within a sector. For example, in the developed regions, electricity and gas are major energy carriers to meet the energy demand of a residential sector. For the same sector, the case of developing countries is generally complex. There, one can find biomass, oil, coal, electricity, etc. Furthermore, the carriers can replace one another and the level is, therefore, important not only to forecast the demand, but also to analyze the impacts of social development policies (Bhattacharya & Timilsina, 2009, pp. 54-55, 66-67), (Stockholm Environment Institute (SEI), 2005, p. 92). At this level, satisfaction of the following condition is mandatory in order to maintain the correct balance.

$$Sector's\ total\ enregy\ consumption = \sum_{j=1}^{c}(Carrier\ consumption)^{j}$$ … … ..*eq. 3. 2*

$Where\ the\ sector\ consumes\ c - numbers\ of\ energy\ carriers$

End-Use Services:

In a system, an end-use service can consume several types of energy carriers. For example, different carriers including, electricity, diesel, gas, etc., serve the energy demand of a public transport system. Their shares in the end-use consumptions clarify the situation and provide an opportunity to consider a prospective fuel switch (Bhattacharya & Timilsina, 2009, pp. 54-55, 66-67). However, the level needed extensive efforts of data collection. Maintaining an overall coherency, the accounting of the base-year carrier consumptions must fulfill the following condition at this level.

$$End - use\ enregy\ consumption = \sum_{k=1}^{type} (Carrier\ consumption)^k \ldots\ldots\ldots.\ldots\ldots. eq.\ 3.\ 3$$

$$Where\ type\ is\ the\ number\ of\ the\ carrier\ types, utilized\ by\ the\ end - use\ service$$

Appliances Population and Use Pattern:

This level is the most challenging one. It requires extensive data and information, which are generally collected through regular surveys. Alternatively, expert judgement is used to approximate the number. The level of the details is significant and important to analyze and assess the impact of; socioeconomic development, energy efficiency, new technology market penetration, fuel switching, demand management, etc.

3.1.1.2 Demand Drivers

Demand drivers are the parameters used to project a system's future energy demand. For the projection, the major drivers are; economic growth, population increase, and life style improvements (IIASA, 2012, p. 390). Generally, historical data and future targets/estimates are used to derive logical assumptions for an assessment of the driver values. The process always involves uncertainty due to its dependency on the future assessments and involvement of human judgement. To overcome this issue, the demand is projected with different sets of assumptions, called scenarios. The factors, that can contribute towards different scenarios, are mainly socioeconomic development (i.e., economic growth, lifestyle, population, etc.) and technological evolution (i.e., efficiency improvements, change in energy intensity, technology market penetration, etc.) (IAEA, 2006, p. 10).

3.1.1.3 Demand Projection

Energy demand of a system is forecasted using the above mentioned details and demand drivers. From the detail of different level, the consumption intensity of the energy carriers in each sector are determined. The future intensities of the carriers incorporate the expected development (e.g., efficiency improvement, social development), fuel switching, etc. Similarly, economic development (i.e., drivers) contribute in the growth of the activities, and ultimately, in the total energy demand. For further clarification, Figure 3. 1 presents a simplified form of the approach (IAEA, 2006, p. 10). In this research, the base year consumption of the electricity was dis-aggregated to a sectoral level, to find the electricity (i.e., energy carrier) intensity in each sector. At this point of dis-aggregation, the following condition was maintained;

$$Base\ year\ consumption = \sum_{i=1}^{s}(Sectoral\ electricity\ consumption)^{i} \qquad \textit{eq. 3. 4}$$

$Where\ the\ system\ consisted\ of\ s - number\ of\ sectors$

To forecast each sector demand, the future sectoral intensities were taken from Pak-IEM[47], which is developed in the TIMES framework (Planning Commission, 2010b, pp. 2-3). For the values of the demand drivers, relevant literature was reviewed. Details of which are given in the "Demand Forecast" chapter of the thesis.

[47] Experts of each sector developed Pak-IEM and the projected intensities involved both data and expert opinion. It was therefore trivial to go down beyond the sectoral intensity level while having readily available information.

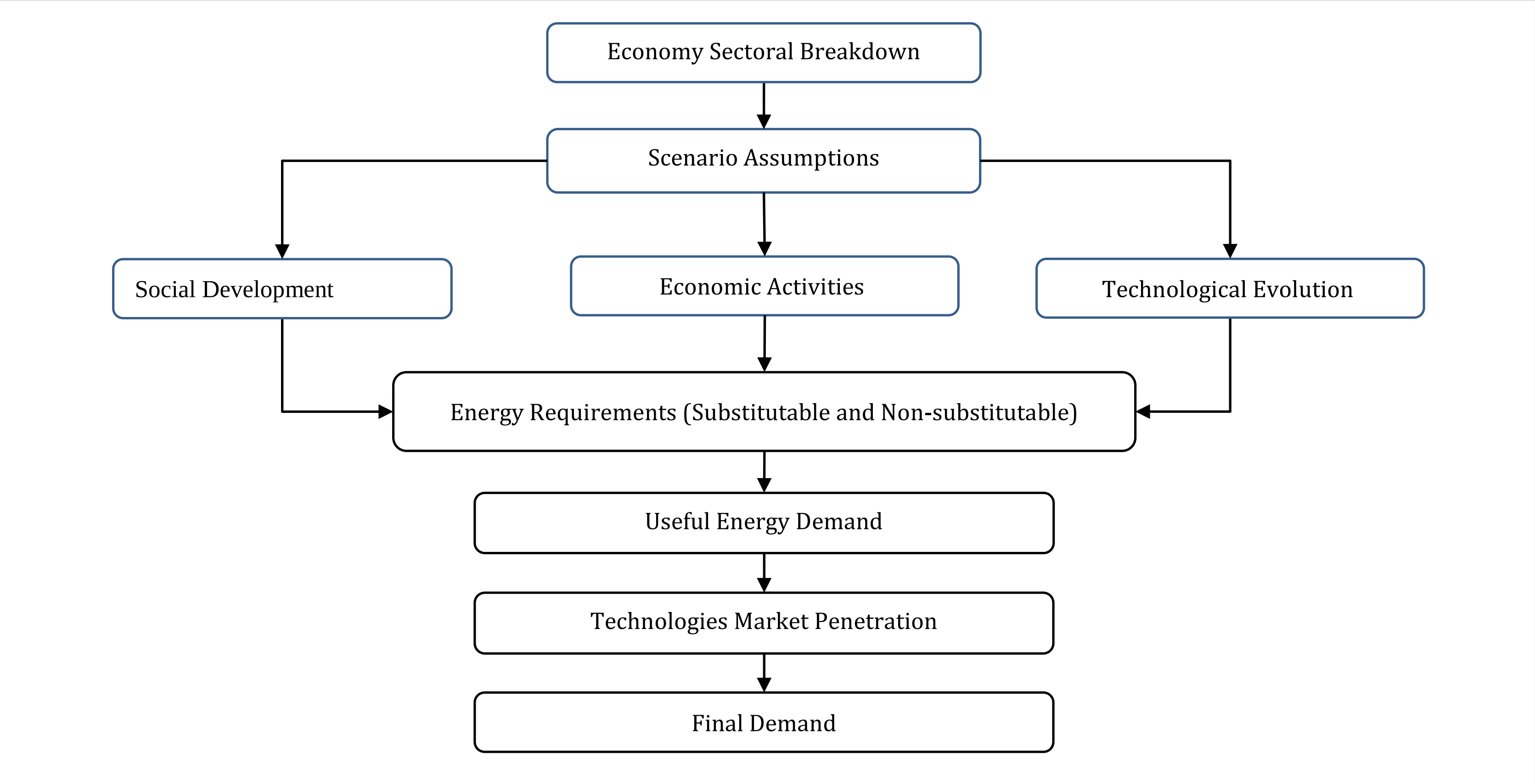


Figure 3. 1: Flowchart of the "End-Use Approach", use to forecast energy demand of a system Source: (IAEA, 2006, p. 10).

3.2 Supply System Modelling

From the literature review in the previous chapter, it is clear that high temporal and spatial resolutions are desirable for an analysis of a renewable resource based supply system. However, if the analysis includes an assessment of transmission system (i.e., power flows) requirements, the two resolutions are necessary irrespective of the supply system (Figure 3. 2) (Schaber, 2013, p. 22). The figure shows common objectives of the analysis and the corresponding required resolutions. For this research, therefore, an hourly temporal and regional approach was chosen.

The review of the literature and modelling framework also revealed that most of the frameworks using high temporal and spatial resolution are limited in access/use. Therefore, the task was performed by developing a time-sequential model[48]. The initial model with a preliminary analysis of the country's solar resources was presented in Pakistan (JAMAL & Hohmeyer, 2014), (JAMAL & Hohmeyer, 2014b). Later, the model was enhanced by improving both the analysis approach and updating the data. The major enhancement in the approach, was the handling of the seasonal storage (i.e., biomass and hydro) system.

In the earlier model, only the intermittent resources (i.e., uncontrolled generations) were handled at an hourly resolution. After utilization of the resources, the residual demand and the seasonal storage supply were considered at an annual resolution, in order to balance the demand. However, the approach ignored the cold start and ramping rate limitations of a biomass based power plant. Later, the seasonal storage was also handled at an hourly resolution, to incorporate the two limitations.

Furthermore, in the early model, the data of the solar insolation and the wind speed were approximated from the monthly mean daily patterns of NASA (National Aeronautics and Space Administration) datasets. In the latter case, the solar patterns were generated by using a mathematical model[49]. For wind speed, measured data were obtained/downloaded from PMD (Pakistan Meteorological Department) and AEDB (Alternative Energy Development Board) Pakistan, for most of the sites. For others, HOMER was used to synthetically generate the wind speed profiles using low resolution information provided by PMD and NASA[50].

[48] I did not find a framework, allowing me to model rive system at hourly resolution and incorporating the grid system of the country.
[49] The method is discussed in the "Solar Resources" chapter of the thesis.
[50] Discussed in detailed in the "Wind Resources" chapter of the thesis.

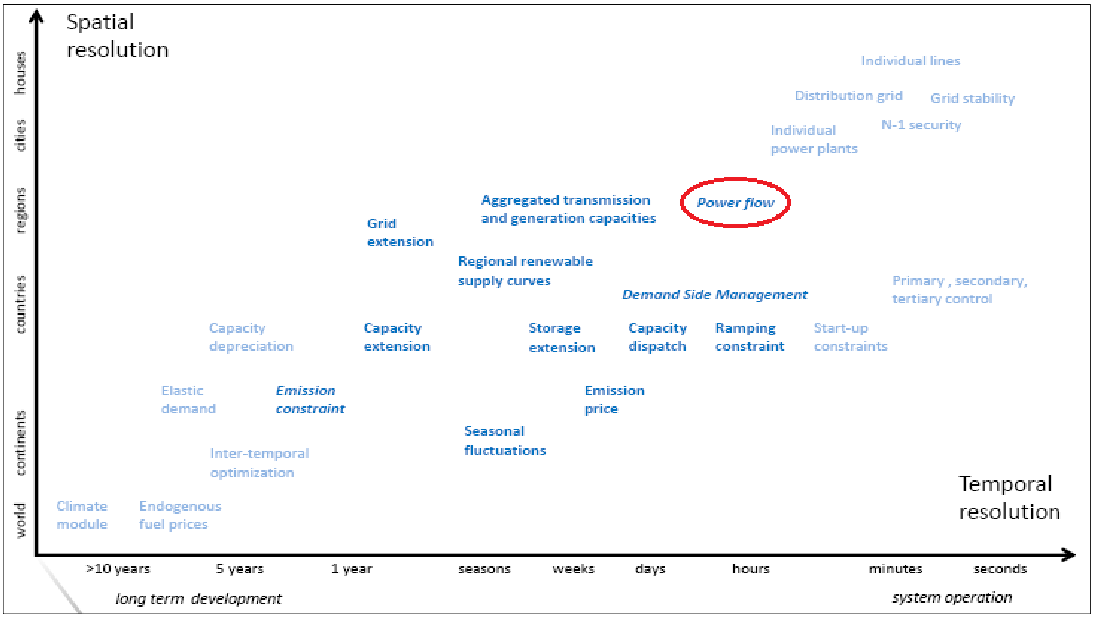


Figure 3. 2: Objective of a demand-supply balance analysis vs. desired spatial and temporal resolutions Source: (Schaber, 2013, p. 22).

3.2.1 Model Characteristics

3.2.1.1 Spatial Resolution

The diversified nature of Pakistan's geography results in an uneven population density across the country. Except Karachi, the load centers are mostly located in the central and eastern parts of the country. To increase the spatial resolution, there were three options, based on the available data.

I. Provincial Level: The first option was to use the country's four provinces with the norther areas (AJ&K and Gilgit) as two additional regions. However, the size of the provinces and their demand are significantly different from one another. For example, the Baluchistan province covered area is more than 40% of the country total land area and has no major load center. In contrast, the Punjab province area is relative smaller (i.e., 25% of the total area), but has the maximum number of load centers (Ministry of Environment, 2010, p. [Table: Land Cover/Land Use]). It was, therefore, more convincing for assessment of power flows to increase the resolution of the two provinces.

II. The second option was to take the covered area of each DISCO (distribution company) as a region. The DISCOs are established within PEPCO (Pakistan Electric Power Company) to serve different load centers (NTDC, 2011, p. 141). However, the resolution was again not a convincing one, as Baluchistan province is being served by a single DISCO.

III. In the third case, the demand data were available at a district level. However, accommodation of the resolution was difficult, as there are about 138 districts in Pakistan (Pakinformation, [n.d], p. [online]), (United Nations, [n.d], p. [n.p]).

Bearing in mind the limitations of each choice, a mix of the second and third options was employed in the model. By taking each DISCO covered area as a region, it was possible to increase the resolution to a reasonable level in the Sindh and Punjab provinces. While the Baluchistan and Khyber Pakhtunkhwa (KP) provinces were divided into four (i.e. Baluch-1, Baluch-2, Baluch-3, and Baluch-4) and two regions (i.e. KP - 1, KP - 2) respectively. In the newly formed regions of Baluchistan and KP, the electricity demand of the districts has been summed up. The sums were then used to distribute the corresponding provincial demand among the newly formed regions.

Currently, the two northern regions of the country, Gilgit Baltistan (GB) and Azad Jammu & Kashmir (AJ&K), are not fully integrated within the national grid. For this analysis, these two regions were also considered as integral parts of the grid system. As a result, seventeen (17) regions were formed (Figure 3. 3) within the country for the analysis.

3.2.1.2 Power Flow Priority

Thermal losses in a transmission line increase with its length and load, depending on what passes through it[51]. As a general principle, therefore, the inter-regional power flows should start from a nearest region, followed by the next one, and so on. In the calculations of the demand-supply balance, the simulation process followed the same principle of prioritization for the imports and exports of power. Furthermore, no limit was applied to the capacity of the transmission lines. The approach was used for a maximum (i.e., efficient) utilization of the resources, and the transmission lines required capacities were assessed accordingly, to accommodate the flows.

3.2.1.3 Hydro Reservoirs Operation

In Pakistan, there are considerable installed, as well as exploitable, potentials of reservoir-based hydropower generation. The reservoirs not only generate electricity, but also fulfill the water needs during the dry period (i.e. winter). It is, therefore, important to use the stored water for power generation and other uses, mainly to fulfill the needs of the agriculture sector. To achieve a suitable operation of the reservoirs, the stored water was distributed in the low inflows period. Additionally, the daily share of the stored water was used during night hours to make up for the lack of PV generations. The approach is further elaborated in the "Methodology Formulation" section of the chapter.

[51] A low load can also results in high losses due to reactive power phenomenon, however, different compensation techniques (i.e., adding capacitor banks, condenser etc.,) are used to stabilize the system.

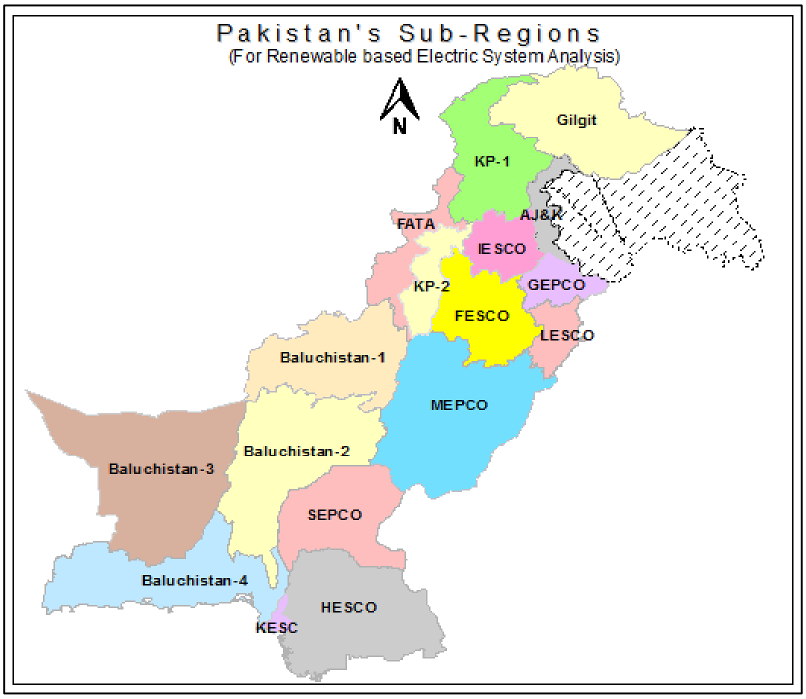


Figure 3. 3: Pakistan's regional map for demand-supply balance analysis, developed by the author using (PDIP, 2015, p. [n.p]) and (United Nations, [n.d], p. [n.p])

3.2.1.4 System Layout

The layout of the method is a cluster of seventeen (17) similar units. Each unit represents a region, the scheme of which is shown in Figure 3. 4. The unit used input information for the calculations of power generations within a region. Initially, the generated power was used to meet the local demand (of a region) at its' maximum possible limit. Next, the spared generations were exported to other regions for direct use and to be stored, if needed. The left over generations after the local use and the exports, were considered as excess generation. The concept is further elaborated on in the following section of the chapter.

3.2.2 Methodology Formulation

The methodology is formulated in independent modules. Each module performed a specific task, and the whole process of the calculation was completed in several steps. In some cases, the calculations started just after entering the data. The results of which were later used by the other modules. For example, the power generation module calculated the power generation after entering the project basic data. Later, the generations were used by the demand-supply balance module. For further clarification, the key process and their formulation are discussed below.

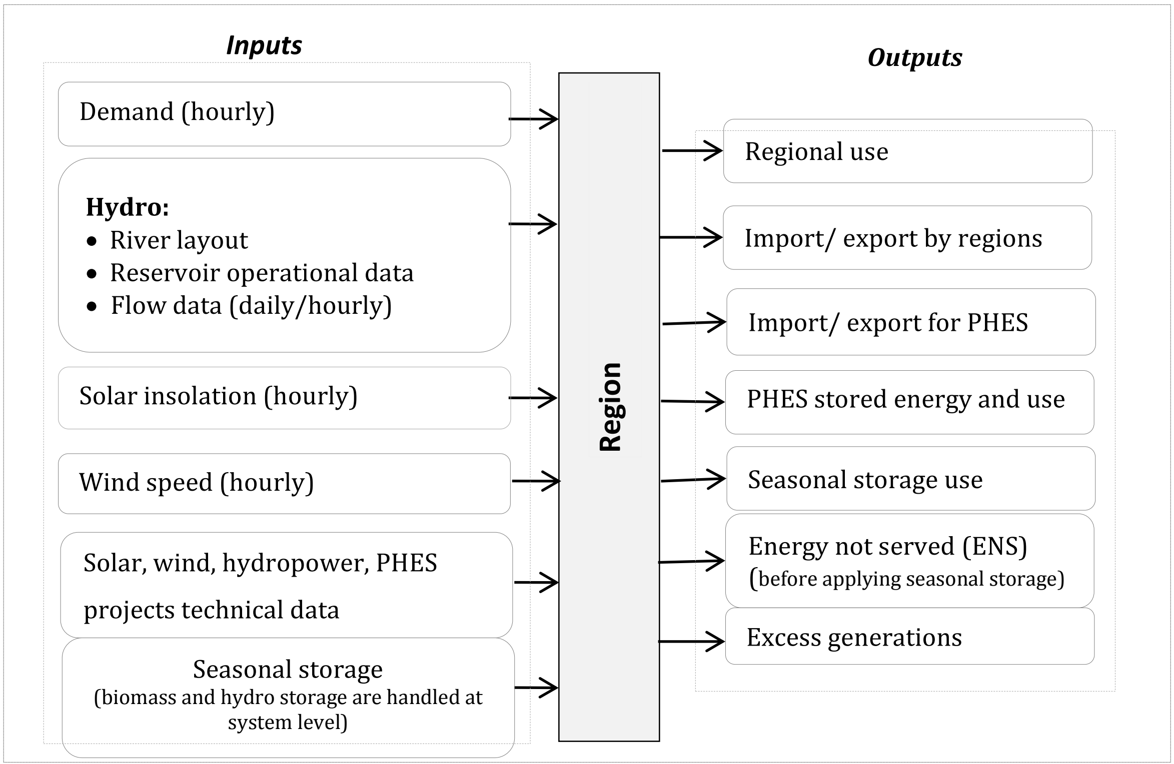


Figure 3. 4: Layout of the "Demand-Supply Model", representing a region with the input data requirements, outputs and the simulation process balance scheme of the model (Demand-Supply Simulation Model)

3.2.2.1 Hydropower and Intermittent Resources Utilization

During simulation, the use of each supply option is independent from the others. For utilization, the resources were selected in the order of wind, solar (i.e., PV), hydropower and PHES. Each region preferred to utilize the local generations at an hourly resolution. Mathematically, eq. 3.5 represents the process.

$$RDA_T^i = RDB_T^i - RG_T^i \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{eq. 3. 5}$$

$Where$

$RDA = Region\ demand\ after\ utilization\ of\ type\ \ 'T'\ local\ resource$

$RDB = Region\ demand\ before\ \ utilization\ of\ type\ \ 'T'\ local\ resource$

$RG = Regional\ generation\ of\ \ type\ \ 'T' resources$

$T = Reource\ type\ (wind, solar, hydel)$

$i = Hour$

Next, the process checked the residual demand of the other regions. To satisfy the demand, the region had to import power from other regions, following the sequence of the first step. The import process followed the before mentioned rule, with the nearest regions receiving prioritization. In the following, equation eq. 3.6 shows a general form of the process.

$$RDAI^i_{T,R_m} = RDB^i_{T,R_m} - IG^i_{T,R_n} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{ eq. 3. 6}$$

$Where$

$RDAI^i_{T,R_m} = Region\ 'm'\ demand\ after\ import\ of\ type\ 'T'\ resource\ from\ region\ 'n'$

$RDB^i_{T,R_m} = Region\ 'm'\ demand\ before\ import\ of\ type\ 'T'\ resources\ from\ region\ 'n'$

$IG^i_{T,R_n} = Spared\ generations\ of\ type\ 'T'\ resource\ in\ region\ 'n'$

$T = Resource\ type\ (wind, solar, hydro)$

$i = Hour$

During the import/export calculations, the module recorded the resource type and transmitted quantity, including transmission losses, in each hour. The exported quantity was then deducted from the supplied resource to maintain the balance. For further clarification, the overall process is presented in a flow chart (Figure 3. 5).The chart shows that each region had equal opportunity to import energy from the nearest region (i.e., with highest priority). For example, if two regions were in needs of energy in an hour. Initially, they both imported energy from nearest regions. Then from the next, and so on. To maintain the demand-supply balance, the model counted transmission losses (TL) in the exported quantity (i.e., $Min\ (AE^h_{(RT,n)}, DB^h_m)$). However, the energy imported and used by a region was a net value ($i.e., Min\ (AE^h_{(RT,n)}, DB^h_m)$ - $Min\ (NAE^h_{(RT,n)}, DB^h_m) * TL_m$). In the case of local resource utilization, the region of utilization and supply were the same (i.e., m=n) and TL were ignored.

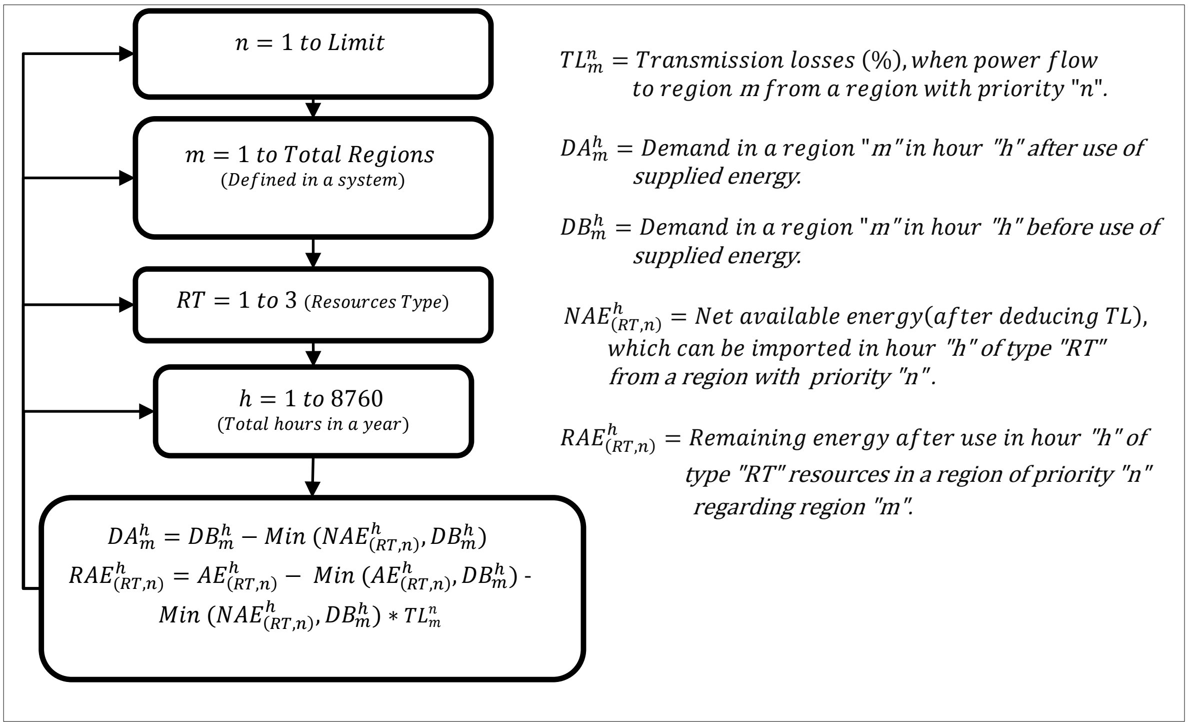


Figure 3. 5: Resources (Wind, PV, Hydro) utilization operation

3.2.2.2 PHES System Operation

After direct use, the left over generations were assumed to be stored by the PHES system, as per storage capacity. In the simulation, the PHES operation was handled at hourly temporal resolution, but with a daily cycle of storage and utilization operation. For description, the overall operation is presented in a flowchart (Figure 3. 6). On a day, each storage system started to store excess hydro, PV and wind generations. For the purpose, the system stored initially the local excess generation, and then imported from other regions. During storage operation, availability of net excess generation (i.e., excluding TL), pumping capacity, and storage capacity were the control variables. In each hour, the stored excess generation is equal to the least one among the three. To maintain a balance, the stored energy, storage losses (i.e., efficiency losses) and TL were deducted from the available energy.

After completion of the storage operation of the day, the utilization operation was initiated. The stored energy was initially used, to meet the demand of the region having the storage system. Later, the energy was supplied to other regions, again following the priorities conditions. Like storage operation, the control variables of the utilization operation were; generation capacity, available stored energy, and demand in an hour. If there was still stored energy, then it was available to the next day.

<u>Flow chart abbreviations:</u>

T/SE_S^D $= Total/\ stored\ energy\ on\ day\ “D”\ in\ storage - system\ “S”$

$NAE_{RT,m}^H = Net\ available\ energy\ that\ can\ be\ stored\ in\ hour\ “H”\ of\ resource\ type\ “RT”$

$RAE_{RT,m}^H = Remaining\ available\ energy\ that\ can\ be\ stored\ in\ hour\ “H”\ of\ resource\ type\ “RT”$

$PC_S^H\ =\ Pumping\ capacity\ available\ in\ hour\ “H”\ of\ storage\ system\ “S”$

$RPC_S^H\ =\ Remaining\ capacity\ available\ in\ hour\ “H”\ of\ storage\ system\ “S”$

$ASC_S^{D(H)}\ =\ Available\ storage\ capacity\ on\ day\ “D”\ in\ hour\ “H”\ of\ storage\ system\ “S”$

$RSE_S^{D-1} =\ Total\ stored\ energy\ of\ the\ previous\ day\ “D-1”\ in\ storage\ system\ “S”$

$RSE_S^D\ =\ Remaining\ stored\ energy\ on\ day\ “D”\ in\ storage\ system\ “S”$

$ASE_S^D\ =\ Available\ stored\ energy\ on\ day\ “D”\ in\ storage\ system\ “S”$

$AD_m^H\ =\ Residual\ demand\ in\ hour\ “H”\ of\ the\ region\ having\ priority\ \text{"m"}\ regarding\ region\ of\ storage\ system\ after\ use\ of\ stored\ energy$

$BD_m^H\ =\ Demand\ in\ hour\ “H”\ of\ the\ region\ having\ priority\ \text{"m"}\ regarding\ the\ region\ of\ storage\ system\ before\ use\ of\ stored\ energy.$

$ASE_S^{D(H)}\ =\ Available\ stored\ energy\ on\ day\ “D”\ in\ hour\ “H”\ of\ storage\ system\ “S”$

$RSE_S^{D(H)}\ =\ Remaining\ stored\ energy\ on\ day\ “D”\ in\ hour\ “H”\ of\ storage\ system\ “S”$

$GC_S^H\ =\ Generation\ capacity\ available\ in\ hour\ “H”\ of\ storage\ system\ “S”$

$RGC_S^H\ =\ Remaining\ generation\ capacity\ available\ in\ hour\ “H”\ of\ storage\ system\ “S”$

$NASE_S^{D(H)}\ =\ Net\ available\ stored\ energy\ on\ day\ “D”\ in\ hour\ “H”\ of\ storage\ system\ “S”$

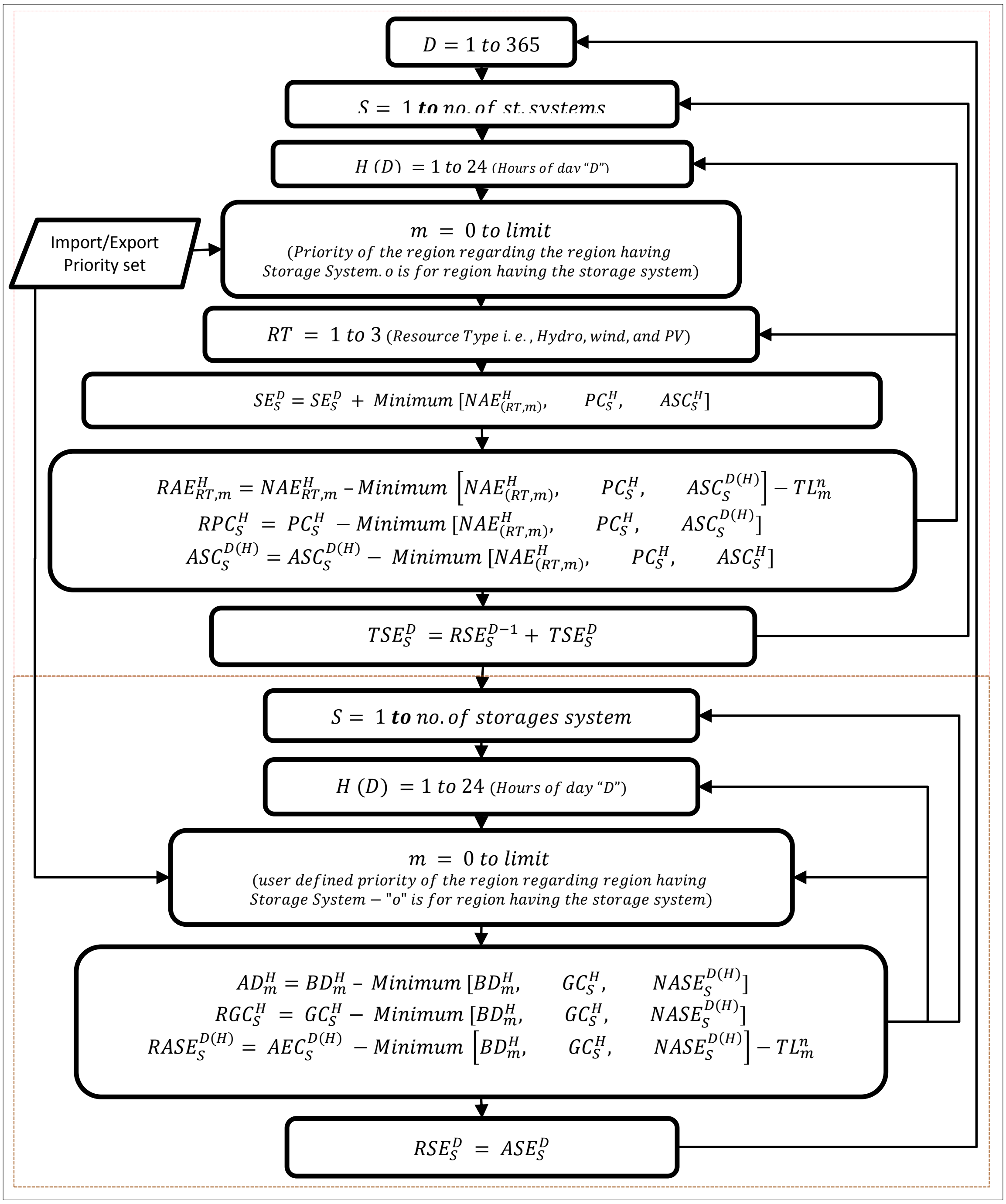


Figure 3. 6: Flowchart showing Pump Hydroelectric Storage (PHES) System operation (Demand-Supply Simulation Model)

3.2.2.3 Hydro Generation

The methodology that was used, involved two independent modules for handling the hydro system. One module handled the operation of the reservoirs, while the other calculated the water flows of the river system and power generation of the RORHP projects. In the following paragraphs, the two processes will be explained.

Reservoirs Operation:

Pakistan is a water stressed country[52] and faces water shortages, particularly to fulfill winter water requirements for the agriculture sector. The situation has increased the worth of stored water, which is optimally used during the period. However, during summer, water inflows in the river system are substantially high[53], and the reservoirs start to fill up.

To distribute the stored water across the year, input parameters were used for controlling the outflows. In addition, a daily share of the water was assigned to the nighttime, to make up for the lack of the PV output as mentioned before. The discharge points of the reservoirs were then linked to their corresponding downstream points on the river system. This concept was important, due to the prospective reservoirs in the system.

The above mentioned two parameters of the operation control, were the storage percentage (SP) and release percentage (RP). The SP was the percentage of full power flow, which initiated the storage process while RP was the same value corresponding to the release of the water. This means that the value of the SP was equal or higher than 1.0 and the value of the RP was less than 1.0. For simulation purposes, an adjustment in the values for each reservoir had changed its operation. In the following paragraphs, the concept is further elaborated upon, with figures and its own flow chart.

I. On any day[54], an hourly full power flows were calculated according to the reservoir water level, using the following equation (Kirtley, 2010, p. 09).

$$Q^h = \text{Full power capacity of HPP } (Watt) / (H^h * \rho * g * \mu) \dots\dots\dots\dots\dots\dots\dots \text{eq. 3. 7}$$

Where;

$Q^h = FPF\ required\ in\ hour\ "h" - (m^3/Sec)$

$H^h = Reservoir\ head\ in\ hour "h" - m$

$\rho = Water\ density\ \left(1000\ {kg}/{m^3}\right)$

$\mu = Power\ generator\ and\ turbine\ system\ efficiency \sim 90\%$ (USDI, 2005, p. [Introduction])

II. Next, the module calculated reference value of storage (RoS) and reference value of release (RoR) processes. These values were derived from the SP and RP, using eq. 3.8 and eq. 3.9.

$$RoS^i = Flow^i_{FP} * SP \dots\dots\dots\dots\dots\dots\dots \text{eq. 3. 8}$$
$$RoR^i = Flow^i_{FP} * RP \dots\dots\dots\dots\dots\dots\dots \text{eq. 3. 9}$$

$Where,$

$RoS^i = Reference\ value\ for\ storage\ operation\ at\ hour\ i$

$RoR^i = Reference\ value\ for\ release\ operation\ at\ hour\ i$

---

[52] Discussed in details in the "Hydro Resource" Chapter

[53] The details are describe in the "Hydro Resource" chapter

[54] The river inflow hourly data was available as daily average i.e., daily means hourly inflow.

$SP = Storage\ input\ parameter$
$RP = Release\ input\ parameter$

III. In the third step, the module compared the hourly inflows in the reservoir with the two reference values. This resulted in the following four possible operational conditions.

Condition-I (Inflow Value > $\boldsymbol{RoS}$): If the Inflow was greater than RoS, a specified percentage[55] of the additional water was stored, but only if the storage capacity was available. During the period, the power plant operated at its full power capacity. If the reservoir had storage capacity, the level as well as the head gradually increased (Figure 3. 7a). The hourly values of the reservoir outflows were adjusted according to the stored water i.e.,

$$Electric\ Generation^{h}(MW) = Full\ power\ capacity\ of\ HPP\ (MW)$$

If the reservoir has sufficient capacity for storing (i.e., $AWSC^{h} >$ (Inflow^{h}-FPF^{h})*SW) then

$$RTSW^{h} = RTSW^{h-1} + (Inflow^{h} - FPF^{h}) * SW$$
$$Outflow^{h} = Inflow^{h} - (Inflow^{h} - FPF^{h}) * SW$$
$$RH^{h} = RH^{h-1} + (Inflow^{h} - FPF^{h})*SW)*HPUSW$$

Otherwise, reservoir stored a fraction of the available water (i.e., $(\text{Inflow}^{h} - FPF^{h}) * \text{SW}$) and the reservoir level reached to its peak level (i.e., completely filled);

$$RTSW^{h} = RFSC\ (Reservoir\ reach\ to\ full\ capacity)$$
$$Outflow^{h} = Inflow^{h} - (RFSC - RTSW^{h-1})$$
$$RH^{h} = RH^{maximum}$$

In the equations;

HPUSW=Head changer per unit stored water (internally calculated).
$AWSC^{h} = Available\ water\ storage\ capacity\ in\ hour\ "h".$
$RTSW^{h} = Reservoir\ total\ stored\ water\ in\ hour\ "h".$
$RFSC = Reservoir\ full\ storage\ capacity.$
$RH^{h} = Reservoir\ head\ (water\ level\ in\ reservoir).$

Condition-II (RoR < Inflow Value < RoS): In this scenario, neither the water is stored nor released. However, the daily inflow water is distributed according to the distribution pattern. Which means that the reservoir status remains unchanged during a complete day operation and the total water inflow on a day “d” is equal to the water released. In each hour, the power is generated by the water flow, determined by the distribution pattern i.e.,

[55] The specified values for storage and release were inputs, and an adjustment in their values with SP and RP helped to achieve a good approximation of the reservoir real/desired operation.

$$Q^h = (Daily\ total\ inflow) * Distribution\ Value\ / \sum_{i=1,d}^{24,d} (Distribution\ Value)^{i}$$

$$Electric\ Generation^h(MW) = Q_h * H_h * \rho * g * \mu/1000000$$

$$RTSW^D = RTSW^{D-1}$$

$$Outflow^D = Inflow^D$$

$$RH^D = RH^{D-1}$$

In case, if hourly share exceed FPF in an hour, the extra water is re-allocate to the other hours of the day. This allocation initiates from hours of high generation toward the lower one to maintain power generation high in the hours of water maximum utilization. During this period, the reservoir level and the head remained unchanged (Figure 3. 7b).

Condition-III (RoR > Inflow Value and Stored Water was Available): When the inflow value was less than RoR, the module released a specified percentage of the stored water. However, this is only possible if the reservoir had stored water. In that way, the reservoir level and the head both gradually decreased. Again, the water was released during the night, with a delay due to the daytime inflows. In this case, the water required to operate the HPP at full power capacity gradually increased due to a decrease in the head (Figure 3. 7c). Therefore, the power plant generation capability decreased. Furthermore, the quantity of daily release is affected by the available stored water in storage i.e.,

If available stored water is more than desired daily share ($i.e., RTSW > FPF^h$*RW*24) then

$$Daily\ released\ share = FPF^h * RW * 24$$

Otherwise,

$$Daily\ released\ share = RTSW$$

and

$$Q^h = (Daily\ inflow + daily\ rel.share) * Dist.Value\ / \sum_{i=1,d}^{24,d} (Dist.Value)^{i}$$

$$\text{Electric Generation}^h(MW) = Q_h * H_h * \rho * g * \mu/1000000$$

$$RTSW^h = RTSW^{h-1} - Outflow^h$$

$$RH^h = RH^{h-1} - (Q^h * HPUSW)$$

$$Outflow^D = Inflow^D + Daily\ released\ share$$

Consequently, in the scenario;

$$Daily\ outflows = Daily\ Inflows + Released\ water$$

Condition-IV (RoR >Inflow Value with no Stored Water Available): In this scenario, the inflows were less than RoR, but the reservoir had no stored water. Hydropower generation was made according to the water inflows and the reservoir head, as well as the storage level were at their minimum level, as shown in Figure 3. 7d. However, the daytime outflows were again delayed until evening for nighttime utilization In this scenario, the head and storage are at minimum level and the total inflow water on day “d” is distributed as per distribution pattern i.e.,

$$Outflow^h\ (Q^h) = Daily\ total\ inflow * Dist.Value\ / \sum_{i=1,d}^{24,d} (Dist.Value)^i$$

$$\text{Electric Generation}^h(MW) = Q_h * H_h * \rho * g * \mu/1000000$$

$$RTSW^h = 0$$

$$RH^h = RH^{minimum} \text{ (i.e., reservoir is at the minimum level)}$$

$$Outflow^D = Inflow^D + Daily\ released\ share$$

The operational algorithm used for incorporating the process, in the model, is presented by the flow chart seen in Figure 3. 9. Using this approach, the overall operation spanning a year of the Tarbela RHPP can be seen in Figure 3. 8, with the above mentioned four operational conditions. In addition, the annual operation patterns of the other reservoirs can be seen in Appendix-A of the thesis. It is important to point out that the module calculated the electric power using eq. 3.7.

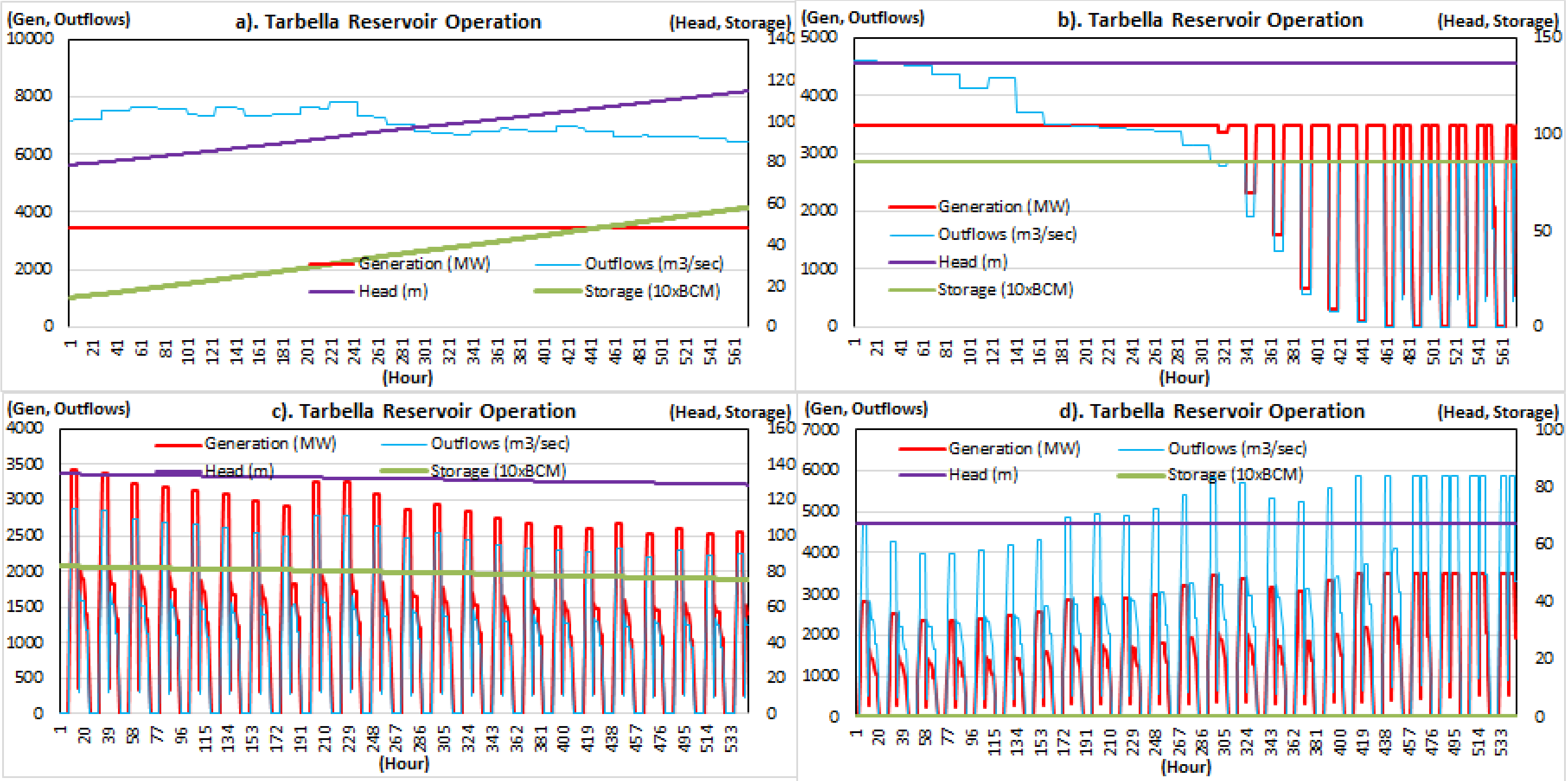


Figure 3. 7: Tarbela reservoir operation: a). high inflow to operate at full power and store the additional water, b). medium inflow neither release the stored water nor store, c). low inflows period and stored water is available, d). low inflow and no stored water is available (simulation)

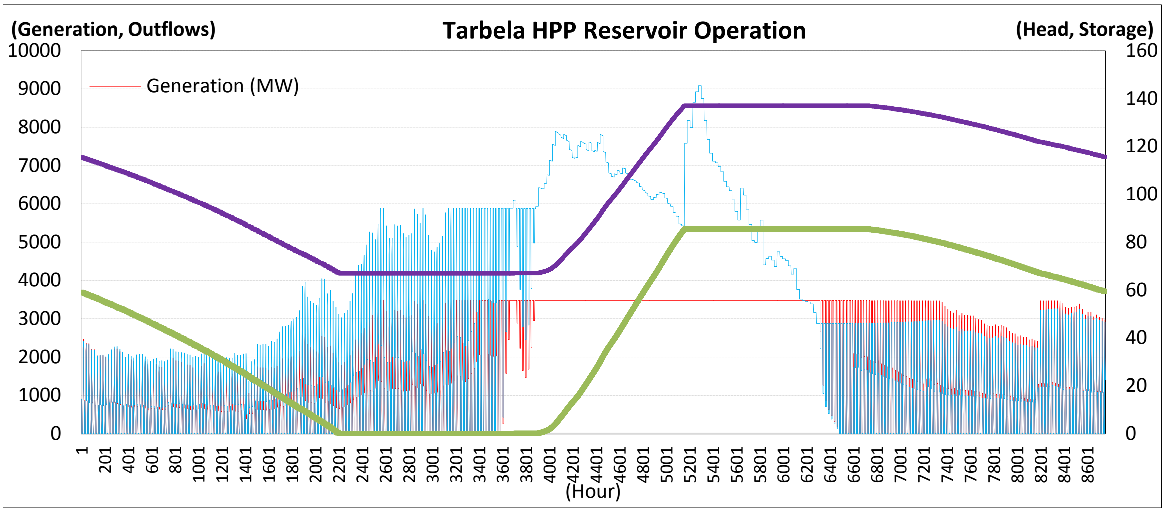


Figure 3. 8: Tarbela reservoir annual operation (Simulation)

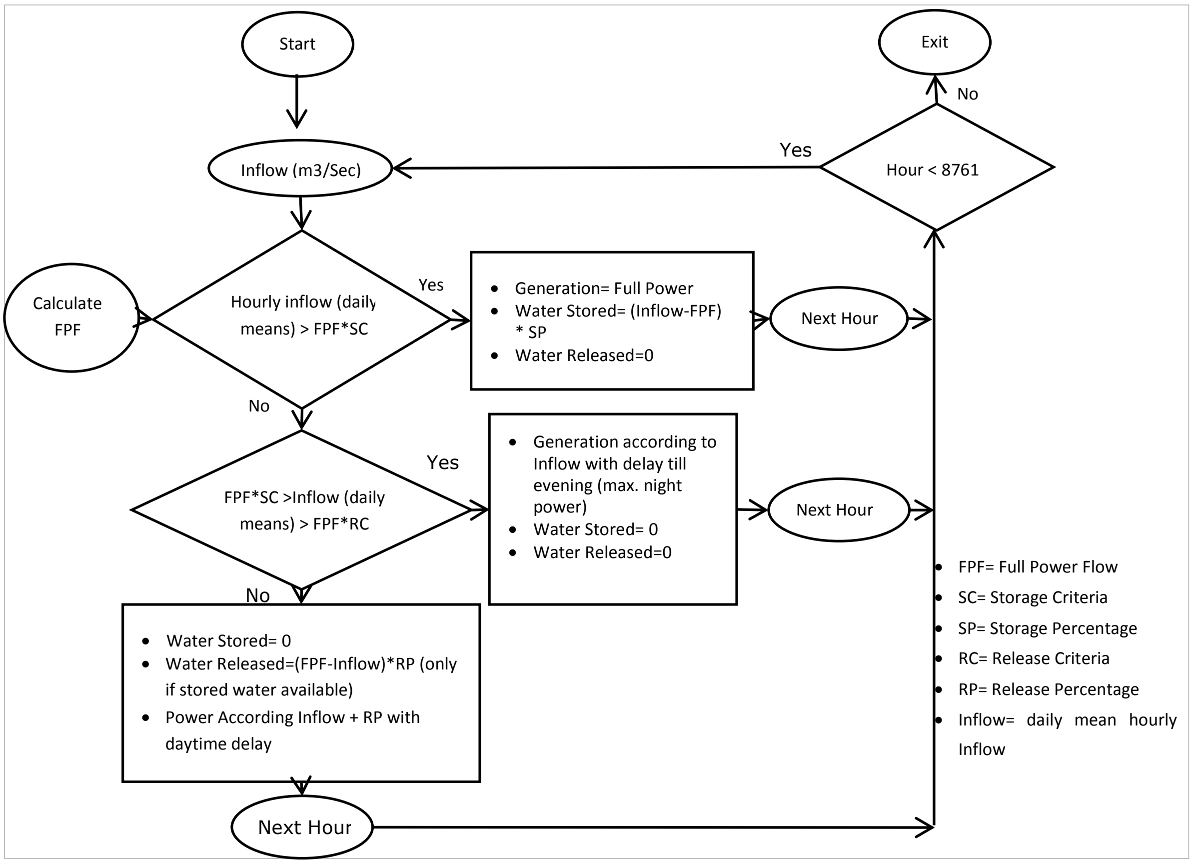


Figure 3. 9: Reservoir based hydropower plant operation

Rivers System:

In the analysis, the river system was handled at the country level, while the hydropower generations were handled regionally. For calculations of the river flows, a parameter(s) was used to link each downstream point with the corresponding upstream point(s), including the reservoir outflow points. The values of the starting upstream points were the percentage of the water that reached to a downstream one and were found using historical data of the water flows (WAPDA, 1975, pp. 17-243). Mathematically, the following equation shows a relationship of a downstream point with the corresponding upstream point(s).

$$Flow_d^i \quad = \sum_{i=1}^{N} Flow_u^i \quad * P_u \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textit{eq. 3. 10}$$

$Where,$
$Flow_d^i = Water\ inflows\ at\ a\ downstream\ point\ in\ hour\ i$
$Flow_u^i = Water\ flow\ at\ an\ upstream\ point\ in\ hour\ i$
$P_u = Relational\ parameter\ between\ the\ two\ points\ (i.e., percentage\ of\ water)$
$N = Number\ of\ inflow\ rivers/tributeries$

Later on, the flows at the different river points were used to calculate the hydropower generations in each region, using eq. 3. 7.

3.2.2.4 PV Electricity Generations

For PV generation, a regional hourly profile of the solar insolation (kW/m^2) was used, with the capacity considered in each regions. Since the capacity changed in each simulation, the power generations were updated accordingly, using the following relationship:

$$Geneation_{Hourly} = P_{Cap} * Hourly\ valur\ of\ insolation \ldots\ldots\ldots\ldots \textit{eq. 3. 11}$$

$Where\ P_{Cap}$ is the PV capacity in a region.

3.2.2.5 Wind Power Generations

Normally, the power generation ability of a wind turbine (i.e., power curve) is given at integer values of wind speed (i.e., V= 3, 4,….. m/sec). The values are based upon the following equation (Mohd, 2011, p. 28).

$$Power = 0.5 * \ Air\ density\ * Turb.area\ * Turb.power\ Coeff. * V^3$$

Where,
$Air\ density = 1.23\ {kg}/_{m^3}$
$Turb.area = \pi(r = rotor\ radius)^2$
$Turb.power\ Coeff \leq 0.59$

In the equation, $\mathrm{Turb.power\ Coeff.}$ depends upon wind turbine design and can vary with wind speed. However, its value can be assumed constant at a specified wind speed. As a result, a simplify form of the equation can be written as follow.

$$Power\ (MW) = Constant_v * V^3$$

At a given wind speed (i.e., in decimal form), the model calculates the constant from the turbine curve at a closest integer wind speed (after rounding) and used in the above equation to calculate wind generation (i.e., power) at the given wind speed.

According to Molly (2011, p. 50), the size (i.e., capacity) of the installed wind turbines significantly vary around the world. He found that at the sites of moderate to strong winds, the installed turbines are in the range of 0.4 to 7.5 MW. In Pakistan, the current operational wind turbines of the two commercial projects are in the range of 1.5-1.8 MW[56]. Furthermore, the frequencies of the low wind speeds are high enough at most of the sites, which back the selection of a turbine having low cut-in speed. Bearing this in mind, the Vestas V110-2.0 MW power curve (Figure 3. 10), was used in the relevant calculations (Vestas, [n.d], p. [online])[57]. The turbine cut-in speed is 2.5 m/sec, while the cut off speed is 25 m/sec.

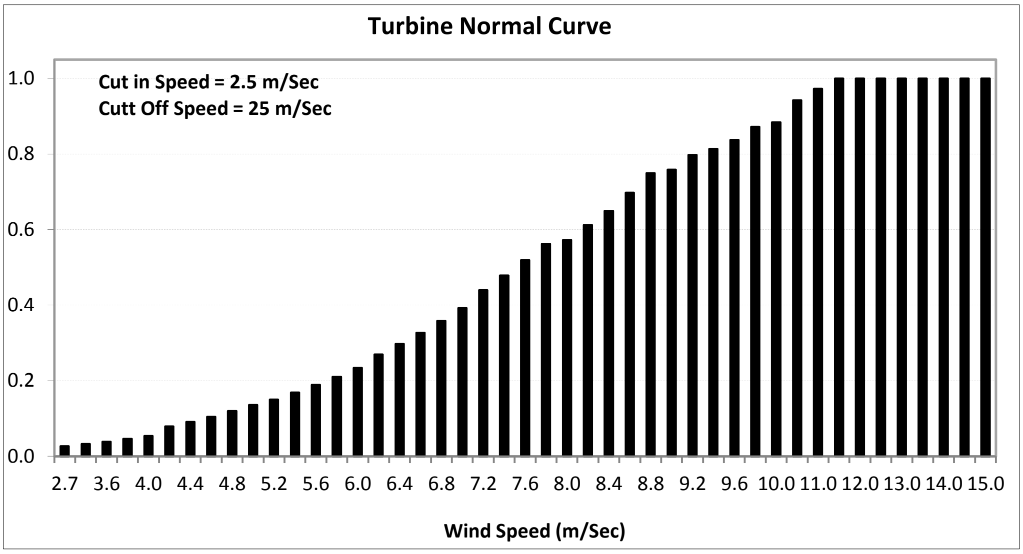


Figure 3. 10: Wind turbine reference normalized power curve
Source: (Vestas, [n.d], p. [online])

3.2.2.6 Seasonal Storage

In each supply case, the detailed demand-supply balances were found after using the generations of the wind, solar, hydro and PHES system at two different PV capacities. First, when the PV capacity was low (i.e., minimum) and overall utilization of the resources were high (i.e., more than 80%). Second, when the PV capacity was high (i.e., maximum), and consequently, the annual utilization factor (AUF)[58] of the system drop (80% >AUF > 50%). In the coming chapters, the two demand-supply situations are referred as low PV capacity (LPC) and high PV capacity (HPC) respectively.

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[56] Already discussed in the chapter
[57] Since policy planning is a continues process, therefore, during implementation, an analysis will be needed with the consideration of site specific physical constrain, economics, financial requirements etc.
[58] The parameter is discussed in a coming section of the chapter.

The residual demand (i.e., demand after wind, PV and hydro utilization) reported in the two demand-supply balances (i.e., at LPC and HPC) were used to assess the seasonal storage requirements. For assessment, biomass based generations and seasonal hydro storage supply system were considered as seasonal storage options, in order to balance the residual demand. The two options were employed at an hourly temporal resolution, more details of which can be found in the "System Simulation and Demand-Supply Balance" chapter of the thesis.

3.2.2.7 Decision Parameter of the Simulation Process

The initial simulation process was an iterative one, which always checked for a parameter to be used for the next round of calculations (or be stopped). This parameter is referred as electricity not served (ENS) in the simulation process and in the results. The process generated a summary of the findings after each simulation, and a detailed analysis was performed only at LPC and HPC for each supply case, as mentioned before. Furthermore, AUF of the supply resource was also calculated to assess the performance of the supply system. In the following, the two parameters are briefly explained.

Electricity Not Served (ENS):

ENS values were not only used as decision parameter, but it also helped in the assessment of the demand-supply situation. Since it was hard to determine or follow the residual demand at an hourly level, the calculation process summed up the hourly residual demand at the end of each iteration (i.e., simulation)[59] and reported them as a percentage of the demand (eq. 3.12). This value is referred as the ENS of the system.

$$ENS = \frac{Resiudual\ Demand\ (before\ appllying\ seasonal\ storage\ options)}{Total\ Demand} \text{...........eq. 3. 12}$$

Annual Utilization Factor (AUF):

Generally, the intermittent and/or uncontrolled nature of renewable resources and variations of the demand result in a mismatch between the two. In the case of Pakistan, the seasonal gaps (i.e., variations) are also prominent. Which means that an inefficient use of the resources is highly probable with an increase of the system dependency on the resources, particularly on the PV generations[60]. To assess the resource wastages, an AUF concept was used. After each demand-supply simulation, AUF values of the resources were calculated using the following relationship.

$$AUF_R^T = \frac{Utilized\ Generations_R^T}{Total\ Generations_R^T} \text{..................................eq. 3. 13}$$

[59] Before applying seasonal storage supply options

[60] The statement is true when there is a fixed demand. The operation can be made efficient while considering a deferrable (i.e., flexible) load.

$Where,$
$Utilized_R^T = \ Energy\, used\, of\ type\ \ 'T'resource, generated\ in\ region\ 'R'.$
$Generated_R^T = Generated\ energy\ of\ type\ \ 'T'resource\ in\ region\ \ 'R'.$

The AUF was calculated for each supply option, in each region as well as of the whole system. During simulations, the regional AUF of the PV resources were important. This helped in the adjustment of their capacities for a next round of the calculations (i.e. increased the regional PV capacities according to their AUFs). For the analysis, the combination of ENS and AUF gave a good insight into the supply system performance. In general, a high value of the system AUF and a low value of the ENS were desired for an efficient operation.

3.3 Transmission Lines Assessment

Modelling and analysis of a power transmission system is a specialized area, for which, advanced commercial frameworks, (e.g., PowerFactory) are available (DigSilent, [n.d], p. [online]). These frameworks needed extensive data and resources in order to perform the analysis at a detailed level. For example, to analyze a contingency plan if a line in a system would break down. Or to assess the system's response in handling a transient, generated within a power system, etc. These kind of analyses were beyond the scope of this research. This research included only an assessment of the required lines, which were used to handle the power flows. For this purpose, an available approach in the literature of electrical power engineering has been used, which is briefly described in the following sections.

3.3.1 Transmission Lines Model

The efficiency of a transmission line is seen in the ratio of receiving and sending end power. To determine the end power, relevant parameters are voltage, current and phase angle at the end. The parameters of the ends are dependent upon a line characteristics (Grainge & Stevenson, 1994, p. 195). Generally, the complexity of calculating the parameters increases with the length of a line. According to Grainger & Stevenson (1994, p. 195), if the length of a line is;

- less than 80 km, use the short length model.
- between 80 –240 km, use the medium length model.
- above 240 km, use the long length model.

However, in the three models, the second one can be used in place of the first one, while the third one is applicable in all of the three cases. To estimate transmission line losses in the lines of different lengths among the regions at the desired load-ability, the third one was used, which can be mathematically expressed, as shown in eq. 3.14 and eq. 3.15 (Grainge & Stevenson, 1994, pp. 212-214).

$$V_S = V_R * Cosh\sqrt{YZ} + I_R * \sqrt{\frac{Z}{Y}} * Sinh\sqrt{YZ} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{eq. 3. 14}$$

$$I_S = V_R * \sqrt{\frac{Y}{Z}} * Sinh\sqrt{YZ} + I_R * Cosh\sqrt{YZ} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{eq. 3. 15}$$

Where,

$V_S = Sending\ end\ voltage$

$V_R = Recieving\ end\ voltage$

$I_S = Sending\ end\ current$

$I_R = Receiving\ end\ current$

$Y = Transmission\ line\ shunt\ admittance$

$Z = Transmission\ line\ impedence$

The values of impedance (Z) and admittance (Y) were dependent upon a line length and layout. In this research, all well-known layouts were considered and their Z and Y values were calculated using the following two expressions (Grainge & Stevenson, 1994, pp. 159,176).

$$Z = R + \mu_0 * f * ln\left(\frac{GMD}{GMR}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{eq. 3. 16}$$

$$Y = \frac{1}{4*\Pi*f*\epsilon} * ln\left(\frac{GMD}{GMR}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{eq. 3. 17}$$

Where

$R = Transmission\ line\ conductor\ resistance\ (Constant - \Omega)$

$\mu_0 = Air\ absolute\ magnetic\ permeability\ constant\ (4 * pi * 10^{-7}\ H/m)$

$\epsilon = Air\ absolute\ permitivity$ (8.85 $*10^{-12}$ F/m)

$f = Power\ system\ frequency\ (50\ Hz)$

$GMD = Geometric\ mean\ distance\ between\ phases\ (meter)$

$GMR = Geometric\ mean\ radius\ of\ the\ line\ i.e. per\ phase\ (meter)$

In the expressions, the GMD and GMR were dependent upon line geometry and phase geometry respectively. The below expressions of eq. 3.18 and eq. 3.19 present the generalized forms of the two parameters, which are applicable to all known types of lines and phase layouts.

$$GMD = \sqrt[3]{D_{12} * D_{23} * D_{31}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{eq. 3. 18}$$

$$GMR = \sqrt[n]{d^{n-1} * GMR_{conductor}} \ldots\ldots\ldots\ldots\ldots\ldots \text{eq. 3. 19}$$

In the equations;

$D_{mn} = Distance\ between\ two\ phases\ m\ and\ n\ (i.e. D_{12}, D_{23}, D_{31})$

$d = Distance\ between\ wires\ within\ a\ bundle\ of\ phase$

$GMR_{conductor} = Conductor\ radius\ (i.e. mentioned\ in\ a\ conductor's\ specifications)$

3.3.2 Line Load-ability

A line load-ability is the maximum electric power, which can pass through the line without violating the limits. Beside transient stability, the load-ability is limited by two major factors. One is the voltage drop and phase shift, which become severe with the increase of the line length. Generally, capacitors and inductors are used at regular length to minimize the phenomena. The second factor is the thermal effect of the electric power, which deteriorates the strength of a conductor and reduces its operational life (MIT, 2011, pp. 39-41).

In 1953, St. Clair introduced a well-known curve termed as the "St. Clair Curve", presented in Figure 3. 11 (Dunlop et al, 1979, pp. 606-607). This curve can be used for the assessment of a line load-ability in terms of surge impedance loading (SIL) of a line, as follows.

$$Line\ load\_ability = St.Curve\ factor * Line\ SIL$$

SIL depends upon a line capacitance and inductance. The values of which were derived from Z and Y, mentioned in the previous section. Using the two characteristic parameters with a line voltage, SIL of the lines at different voltage levels, were found as follows:

$$SIL = V_R^2 * \sqrt{\frac{C}{L}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad eq.\ 3.\ 20$$

Where

$V_R = Recieving\ end\ desired\ voltage\ (generally\ 0.95 - 1.05\ times\ of\ line\ Voltage)$

$C = Transmission\ line\ shunt\ capacitanc$

$L = Transmission\ line\ inductance$

3.3.3 Requirements of the Transmission Lines

From the demand-supply simulation, the inter-regional flows were revealed. The flows helped in finding the values of the maximum power flow in all of the transmission line corridors. Using the values of maximum flow and load-ability, the required number of lines in each corridor, were assessed as follows:

$$Number\ of\ lines = \frac{Maximum\ power\ flow\ through\ a\ tranmssion\ corridor}{Load\_ability\ \ of\ a\ line\ with\ a\ rated\ voltage\ V}$$

$Where\ V = 220\ kV, 500\ kV, 765\ kV\ and\ 1000\ kV$

In the calculations, a general rule was applied in order to decide the number of lines that belonged to each specific voltage level. Accordingly, if the number of required lines exceeds 05, there would be a switch to a higher level of voltage. At 1000 kV (the final voltage level), the number of lines were not restricted, as there was no higher level to switch it. This concept is further elaborated on in the results i.e., the "System Infrastructure" chapter of the thesis.

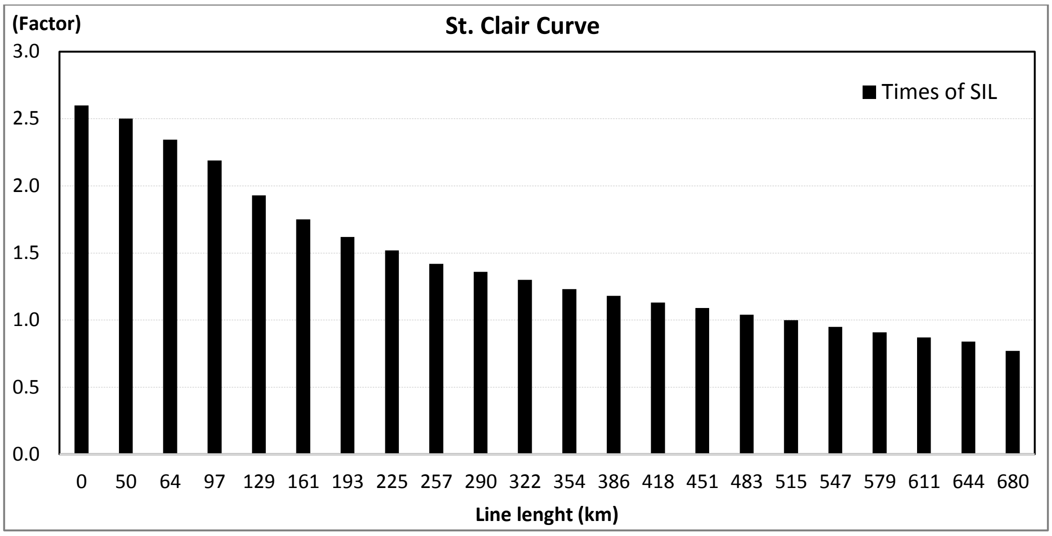

Figure 3. 11: St. Clair Curve for an assessment of a transmission line's load-ability in terms of its SIL
Source: (R.D.Dunlop et al, 1979, pp. 606-607)

3.4 Supply Cases Discounted Cost Assessment

The installed capacity and transmission system requirements changed in the supply cases. To compare the cases based on their discounted cost, the MESSAGE framework was used[61]. In the previous chapter, general characteristics of the framework class were already discussed. Here, therefore, only a brief overview of MESSAGE is given in the context of its use in the research, with a layout in Figure 3.12 for general information (JAMAL, 2015, p. 59).

Since the framework temporal resolution is low, it has not been used for the demand-supply balance calculations. However, the output of the previously described approach (i.e., hourly simulation) helped in overcoming this issue. From the simulation, the required installed capacity and effective capacity factors[62] of the cases were found. The findings were used to derive the weighted values of the techno-economic and other parameters (i.e., plant life, investment cost, operation cost, etc.). These weighted parameters were used in MESSAGE in order to estimate the discounted cost of each case[63].

[61] The software and permission of use has been obtained from IAEA.
[62] Effective capacitor means the factors which is derived on the basis of utilized generation instead of total generation.
[63] The concept of weighted parameters is further elaborated in the “System Infrastructure” chapter.

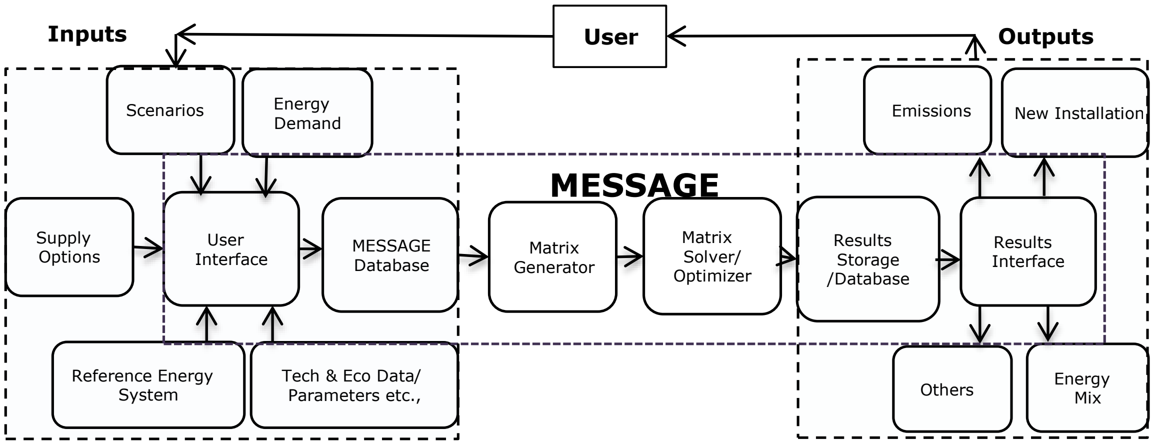

Figure 3.12: MESSAGE layout and its working environment
Source: (JAMAL, 2015, p. 59)

3.5 Methodology Overall Flow Chart

From the above discussion, it is clear that the calculations were performed in different steps, to find the results. For further clarification, Figure 3. 13 presents the flow pattern of the calculation course, with major input and output information. In the figure, the highlighted (i.e., bold) values represent the findings, which were necessary to answer the research questions. The chart shows that the values of the demand forecast were used, both by hourly demand-supply balance[64] and by the MESSAGE framework. As the figure shows, the hourly balance outcomes;

I. helped in finding resource contributions and capacity requirements,
II. were used for transmission lines assessment,
III. were used to derive weighted input parameters for the MESSAGE framework.

[64] A general name CPRESS (100 Percent Renewable Electric System Simulation) is used, with expectation to be used as a general modelling in the future.

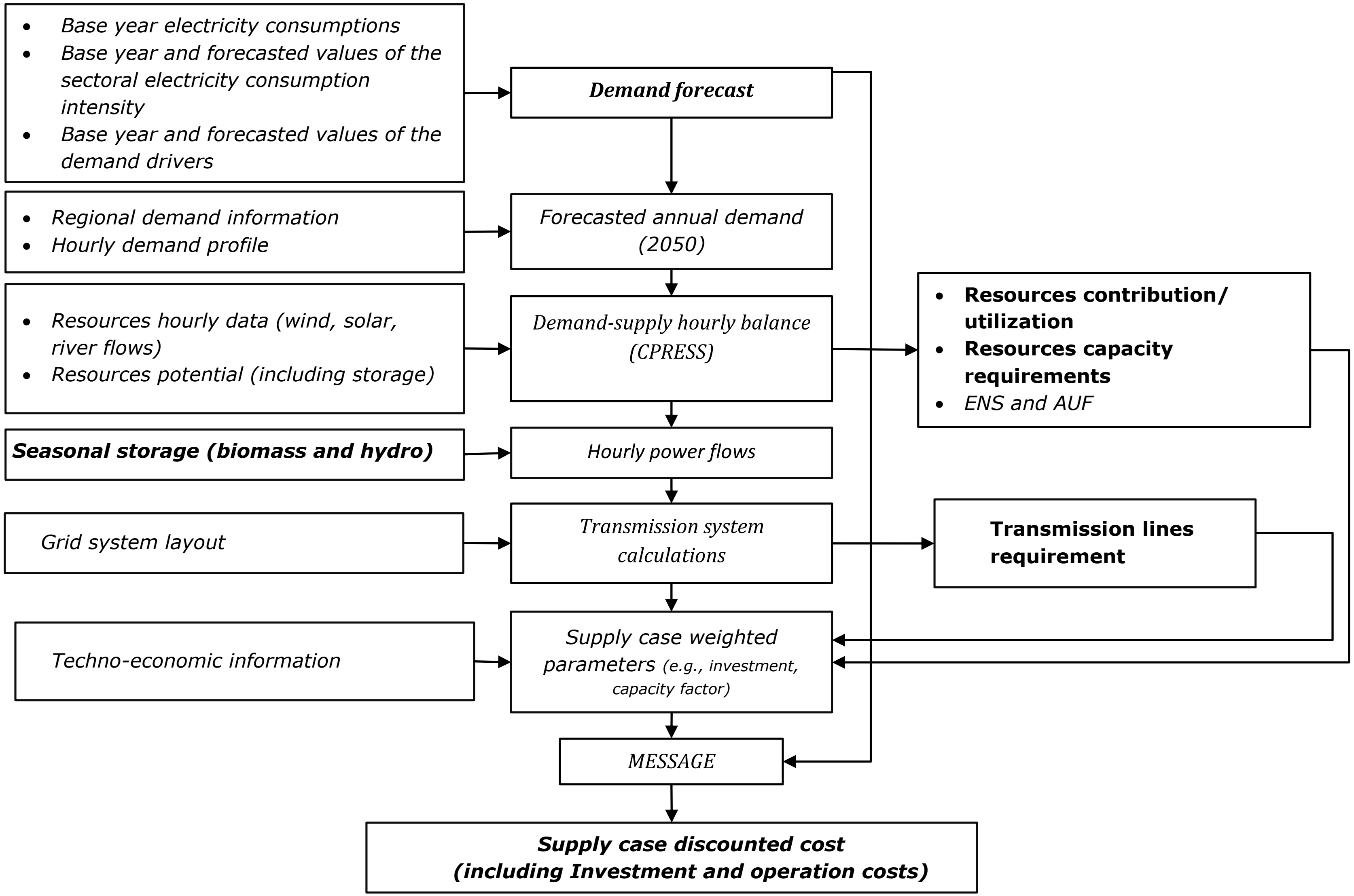

Figure 3. 13: A flow chart of the research analysis methodology and approach

3.6 Chapter Summary

To achieve the desired objective, the calculations were performed in several steps. Beginning with demand, it was forecasted using sector wise projection with values of the electricity consumption intensity from the country energy model (i.e., Pak-IEM). For the calculation of the demand-supply balance, no framework/tool was found/accessible to incorporate hourly temporal and regional spatial resolutions, as desired for the study. Consequently, a generic supply model was developed for this purpose. This model was used, in order to assess the resource contributions, installed capacity requirements and power flows across the country. The power flows were then used with techniques available in the literature of the electric power engineering, to estimate the transmission line requirements. Finally, the outcomes of the calculations were used with techno-economic information to compare the cases based on a total discounted system cost (TDSC). To find the TDSC of each case, the MESSAGE framework was used.

Chapter 04: Pakistan: A Brief Introduction

This chapter briefly presents some relevant information about Pakistan and its energy system. The information can be helpful while passing through the upcoming details of the thesis, particularly the details of the renewable resources in the country. Furthermore, there is a brief summary of the recent short-term renewable energy policy of Pakistan at the end of the chapter.

4.1 Basic Information

Pakistan is a South Asian country, and located in the arid and semiarid zones (Farooqi et al., 2005, pp. 12,16). It came into being in 1947, after the independence and division of the United India (United Nations, 1968, p. 7). On the global map, the country lies in the range of 24^o-37^o N and 61^o -75^o E[65] as shown in Figure 4 1 (Rasul et al., 2011, p. 1). The neighboring countries of Pakistan are India, China, Afghanistan, Iran, and in the south is the Arabian Sea. The country total area is 796,095 km^2, including the affiliated territories and sea area (IOM, 2014, p. 3). Pakistan is the sixth most populous country of the world and had a total population of 188.02 million by 2014. The share of the rural community in the population is about 61.4%, where agriculture is a major livelihood (Ministry of Finance, 2014, p. [Table 12.2]).

Figure 4 1 : Pakistan's geographical position on the globe map
Source: (Google, [n.d(a)], p. [online])

[65] The capital (i.e., Islamabad) coordinates are; 33°40'N and 73°10'E (Warwick, 2007, p. (Sec.G)1)

4.1.1 Geography

Pakistan’s geography is extremely diversified and varies from mountain ranges to plane deserts. The country shares three well-known mountain ranges (i.e. the Himalaya, the Karakorum, the Hindukush) in the north and the northwest, as shown in Figure 4.2 (Word Press, [n.d], p. [online]). In Pakistan’s territory, the ranges are of substantial height and have many of the world’s highest peaks. In contrast, the south and southeastern parts are mostly flat. There are also the famous deserts of Tharparkar and Cholistan. In the central parts (i.e., between the north and south), there is an abundance of land, which provides opportunities for agrarian activities (Ministry of Environment, 2010, p. [Table: Land Cover/Land Use]).

4.1.2 Climate

The geographic diversity of Pakistan results in substantial differences of weather intensity. During winter, the northern areas are very cold, and the minimum temperatures drop below freezing by 20-25^{o}C (Abbas et al., 2002, p. 2). The weather of these areas is generally mild during summer. In contrast, the climate of the extreme southern areas is moderate during winter and extremely warm in summer. For example, in May 2010, a heat wave resulted in a temperature of 53.5^{o}C near Larkhana[66] (WMO, 2013, p. 9). To show the climate diversity, a map of the country climate zones is presented in Figure 4. 3 (Sethi, 2007, p. 23).

The precipitation rate in the northern areas is high and regular throughout the year, but decreases significantly when moving toward the south, as indicated in the figure. However,

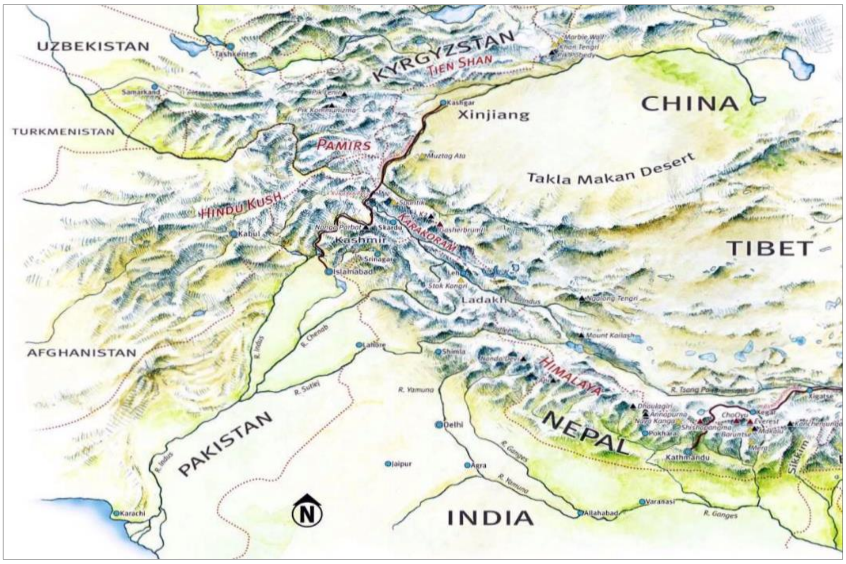

Figure 4.2: Pakistan’s major mountain ranges; the Himalaya, the Karakorum, and the Hindukush (Word Press, [n.d], p. [online])

[66] This is the world fourth highest recorded temperature in the world. The world highest temperature 56.7^{o}C was recorded on 10 July 1913 in California, USA (Guinness, 2012).

during the monsoon period (July-September), rainfalls intensify across most parts of the country, which contributes to frequent flooding in the river system[67].

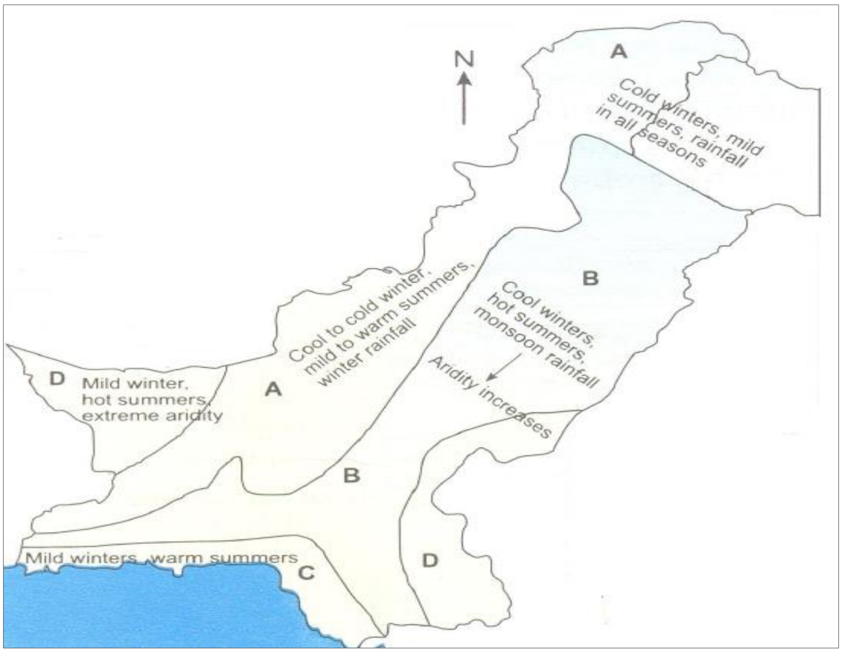

Figure 4. 3: Climate zones in Pakistan
Source: (Sethi, 2007, p. 23).

4.2 Pakistan's Energy System

4.2.1 Primary Energy Supply Mix

Pakistan's total primary energy consumption, as of the year 2011-12, was 64.73 million toe (752.8TWh), as discussed in the introductory part of the thesis. In the total, the share of imports in the year was roughly 31%, mainly in the form of oil. In the consumed oil and coal category, there were also limited shares of indigenous energy resources. Currently, the major indigenous resource is natural gas, which fulfilled 49.5% of the primary energy demand by the year, as shown in Figure 4. 4 (HDIP, 2013, p. 04). In the electric supply system, the shares of gas, oil, and hydropower dominated the system[68].

[67] "Pakistan's Hydro Resource" chapter of the thesis contains detailed information, regarding the flooding phenomenon in Pakistan.
[68] "Demand Forecasting" chapter of the thesis describes the electricity consumption in details.

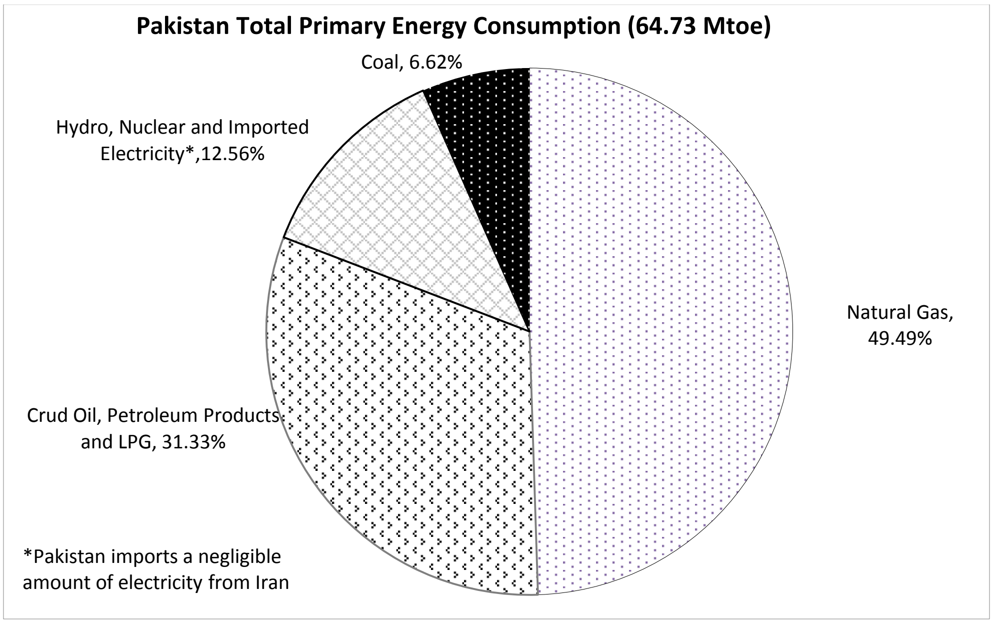

Figure 4. 4: Pakistan's total primary energy consumption in the year 2011-12
Source: (HDIP, 2013, p. 04)

4.2.2 Fossil Fuel Resources and Reserves

In the year 1990-91, a huge resource of coal was discovered in southern Pakistan (Ahmad, 2004, p. 03). According to the exploratory efforts, the resources found there are around 175.51 billion tonnes (PPIB, 2008, p. 05). However, as of now, the country has not initiated mining activities at the site. The major hurdles in the exploitation are as follows: (PPIB, 2008, pp. 1,8,12);

- The coal quality is the lowest as graded (i.e., lignite) by international standards.
- The overburden of the resource varies from 114 to 200 meter.
- The project requires a huge initial investment. By 2004, RWE, Germany assessed 1.7 to 2.0 billion US$ investment to develop a 1000 MWe mine-mouth power generation facility. The investment includes the costs of mine development resources (i.e., machinery) and power plant construction.

In addition to Tharparkar, there are other sites of the same coal type, and the country's total resources are about 185.5 billion tonnes (PPIB, 2008, p. 05). Pakistan's oil and gas reserves are limited. In the following, TABLE 4. I present a summary of the fossil fuel reserves/resources potential, production, and consumption[69].

[69] Reserves generally means a known quantity through exploration efforts, while resources involved estimation. For interested one, US Geological Department provides details information on the topics.

TABLE 4. I: Pakistan's indigenous energy reserves and resources (by 2012)

Energy Carrier	Reserves (Mtoe)	Resources (Mtoe)	Annual Production (Mtoe)	Annual Consumption (Mtoe)	References
Oil	141.18	-	3.3	9.6	(HDIP, 2013, pp. 3,11-16)
Gas	1,114.44	-	32.0	32.0	(HDIP, 2013, pp. 3,53-56)
Coal	1,543.53	832,167.13	1.4	4.3	(HDIP, 2013, pp. 3,75-76)

4.2.3 Electric Power Supply Current Situation

In recent years, the electricity supply system of Pakistan has badly failed to serve the demand. An Investigation of the system identified poor management, circular debt, and financial constraints as the core issues. In response, the GOP initiated a program to progressively commercialize and improve the system (GOP, 2013, pp. 03-07). Meanwhile, the shortage of electricity has resulted in load shedding, and indirectly, in initiatives towards renewable resource development in Pakistan[70].

4.3 Renewable Energy Development in Pakistan

4.3.1 Renewable Energy Policy of 2006

In 2006, the GOP introduced a short-term policy for the promotion and development of the renewable resources. It is difficult to discuss all of the details here; therefore, a short summary of the policy is presented below (Ministry of Water & Power, 2006, pp. 05-21);

I. The experience of the policy will be used to formulate a framework for the future development of the resources in the country.

II. A private investor can develop a renewable energy project, having any one of the following statuses;

- An independent power producer (IPP), to supply generated power to the national grid.
- An owner of a captive power generation facility, based on the resources, to sale extra generation to the DISCOs.
- An Isolated stand-alone generation facility[71].

III. The DISCOs will buy renewable generated power from a supplier under all conditions[72].

IV. An integration of a renewable energy generation facility to the grid system is permitted at different voltage levels[73], as per availability of the connection and power generation conditions.

70 Status of RE resources and development in Pakistan are briefly discussed in the corresponding chapter of each resource.

71 Most probably, to promote RE based generation in remote areas, where grid connection is not available

72 Currently, the system is highly regulated and there is no concept of spot pricing etc. Furthermore, the share of renewable (intermittent resources) is not high, and it is convenient to use their generation first.

73 Mentioned voltage levels are 220 kV, 132 kV, 11 kV and 400 Volt

4.3.2 Dedicated Entities

There are several dedicated entities in Pakistan, which are working towards the development of renewable resources. Their activities intensified recently, with the development of the technologies. Some of the more prominent entities are as follows;

- Alternative Energy Development Board (AEDB) is a government body and works for the resources development in the country (AEDB, [n.d], p. [online]). The board is currently working on the resources re-mapping project with the World Bank (ESMAP, [n.d], p. [online]).
- RAEP (Renewable & Alternative Energy Association of Pakistan) and PRES (Pakistan Renewable Energy Society) are non-profit organization to promote the resources through conferences and other activities (REAP, [n.d], p. [online]), (PRES, [n.d], p. [online]).
- PCRET (Pakistan Council of Renewable Energy Technologies) is a subsidiary of the Ministry of Science and Technology and works on the technical aspects of the technologies (PCRET, [n.d], p. [online]).
- For the development of the resources, a few NGOs (Non-Governmental Organizations)[74] are also working, particularly to promote clean technologies of biomass utilization in the rural areas of the country.

Additionally, PMD (Pakistan Meteorological Department) is specifically involved in the exploration efforts of the wind resources.

4.4 Chapter Summary

Pakistan is a South Asian country with an unusually diversified geography and climatic. The country is a net importer of energy, mostly in the form of oil. Presently, the country is highly dependent on indigenous natural gas resources and imports a reasonable quantity of oil to meet the energy demand. In addition, the country also has an abundance of untapped resources of low quality coal.

For the last several years, the power supply system of the country has struggled to meet the demand. Consequently, the GOP initiated reforms in the power system. Meanwhile, to promote the renewable resources projects, Pakistan has also introduced a short-term renewable energy policy. The main purpose of which is to use the experience for framing a long-term policy.

[74] The NGOs are mentioned in the “Biomass Resources” chapter of the thesis.

Chapter 05: Pakistan's Hydro Resources

Pakistan has a large potential of hydropower generation, mostly in the northern areas. In these areas, dozens of tributaries either originate or enter into Pakistan[75]. They merge during their downstream course and form the country's river system, which flows from the north to the south. The river's water is used for different purposes, including; power generation, irrigation, industrial processes, etc.

In this chapter, the river system is introduced in order to give an idea of the hydropower potential in Pakistan. The description can be helpful when assessing the frequent flood phenomenon and needs of hydro reservoirs in the country. This chapter also discusses the existing reservoir based hydropower plants (RHPP) and total potential of hydropower generation in the country. At the end of the chapter, the potential of pump hydroelectric storage (PHES) and seasonal hydro storage are discussed.

5.1 Hydro Resources

5.1.1 Indus Rivers System

The river system of Pakistan is generally referred to as the Indus River System (IRS). It consists of six major rivers (i.e., Sutlej, Ravi, Chenab, Jhelum, Indus, Kabul) and three well-known tributaries (i.e., Kurram, Gomal, Swat[76]). They all originate fully or partially outside of the country, as shown in Figure 5. 1 (Yakub et al., 2015, p. 9). In addition, there are a few relatively small locally originated tributaries, but their flows are generally only noticeable during a high rain period.

The five major rivers or their tributaries originate in the mountain ranges of the Hindukush, Karakorum and Himalaya (Tahir et al., 2011, p. 2275). Their tributaries are transboundary and pass through the areas, which are either under Indian control and/or disputed between India and Pakistan. The sixth one (i.e. the Kabul River) partially originates in Pakistan. The total catchment area of IRS is 1,138,800 km^2, of which around 52.9% is in Pakistan, 33.8% in India, 6.76% in China, 6.4% in Afghanistan and a negligible (i.e. 10 km^2) in Nepal (United Nations, 2009, p. 141).

[75] The border between Pakistan and India in the region is still disputed and referred as line of control.
[76] It is referred as river than tributary and merge to Kabul River.

Figure 5. 1: Pakistan's Indus Rivers System layout regenerated by the author
Source: (Yakub et al., 2015, p. 9)

5.1.2 Indus Water Treaty

In 1947, the United India became independent, but in the form of two states (i.e., India and Pakistan). A few years later, the international community realized use and control of the water resources could become a potential reason for conflicts between the two neighbor countries. Consequently, the World Bank brokered a treaty between them in the year 1960. This treaty is termed as the Indus Water Treaty (IWT). According to the treaty, India owns the rights of the eastern rivers (i.e. Ravi, Sutlej, Beas[77]) utilization and control, while the western rivers (i.e. Indus, Jhelum, Chenab) rights were given explicitly to Pakistan (World Bank, 1960, pp. 4-7).

Since then, the flows of the eastern rivers has significantly reduced in the territory of Pakistan. Except the high flow period of summer (i.e., monsoon), their flows are very low (Nosheen & Begum, 2012, p. 274). During monsoon season, the flows in the entire river system are very high, which frequently result in a flooding situation.

The eastern rivers are linked to the western rivers through a canal system (Figure 5. 2). The system is used to manage the demand of the eastern parts, using the western rivers water (ADB, 2013, p. 6). The canal system also helps in the minimization of flood intensity. Furthermore, a reasonable micro hydropower generation potential is also identified along the course of the canals.

[77] River Beas join River Sutlej before entering to Pakistan i.e. does not enter as separate river

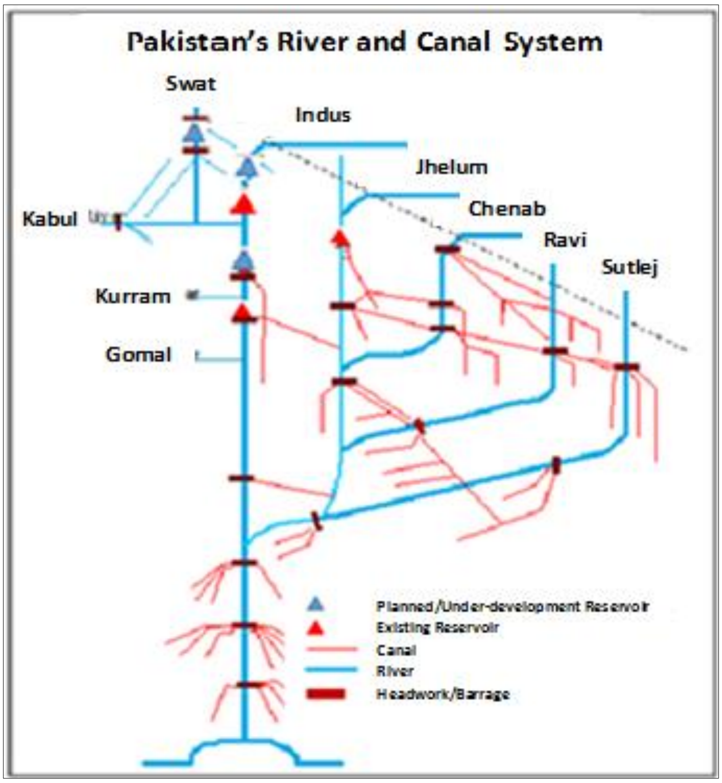

Figure 5. 2: Schematic diagram of the IRS basin and its canals system regenerated from (ADB, 2013, p. 6).

5.1.3 Water Flow Conditions

The variations of water flows in the river system of Pakistan are significant and can be classified by two seasons (i.e. summer and winter). During summer, the flows are high due to the following major reasons (Yakub et al., 2015, p. 10);

I. The catchment area of Pakistan's river system is mainly comprised of the Tibetan Plateau, where the high temperatures of summer cause the melting of the glaciers. As a result, the flows in the upper tributaries of the IRS increase.

II. The catchment area receives a substantial snowfall during winter, which melts down in summer and contributes to the flows.

III. During summer, a series of heavy rainfalls (i.e. monsoons) start in the Indo-Pak region, which further increases the flows.

A combinations of the three phenomena frequently results in a flood, which damages crops and infrastructure in Pakistan. According to GOP (2010, p. 14), more than 80% of the total water pass through the system during the period. In winter, rainfalls are the main source for replenishing the system and the flows significantly decrease. Consequently, a shortage of water takes place in the rivers, and the stored water is used to meet the demand. In the following sections, the flow patterns of the major rivers are briefly discussed.

5.1.4 Major Rivers Flow Patterns

Eastern Rivers

As mentioned earlier, the eastern rivers of Pakistan (i.e. Sutlej and Ravi) remain almost dead during the year. The rivers have occasionally high flows during summer (Nosheen & Begum, 2012, p. 274). However, in that period, there are high water flows in the overall river system of Pakistan. During this period, the flows in the eastern rivers are less needed by the country.

Chenab River

The Chenab River flows through a relatively flat terrain after entering into Pakistan. There are only few potential sites of mini and micro hydropower projects along its course. However, the river is important to charge the canal system for irrigation (Bandaragoda & Rehman, 1995, p. 11). For its flow pattern and volume assessment, Figure 5. 3 presents the daily mean flows of the year 2013 recorded at Marala, Pakistan (WAPDA, 2013, p. [Daily Reports]). Its catchment area receives enough rainfalls during the monsoon season, and the sudden rise can be attributed to that period.

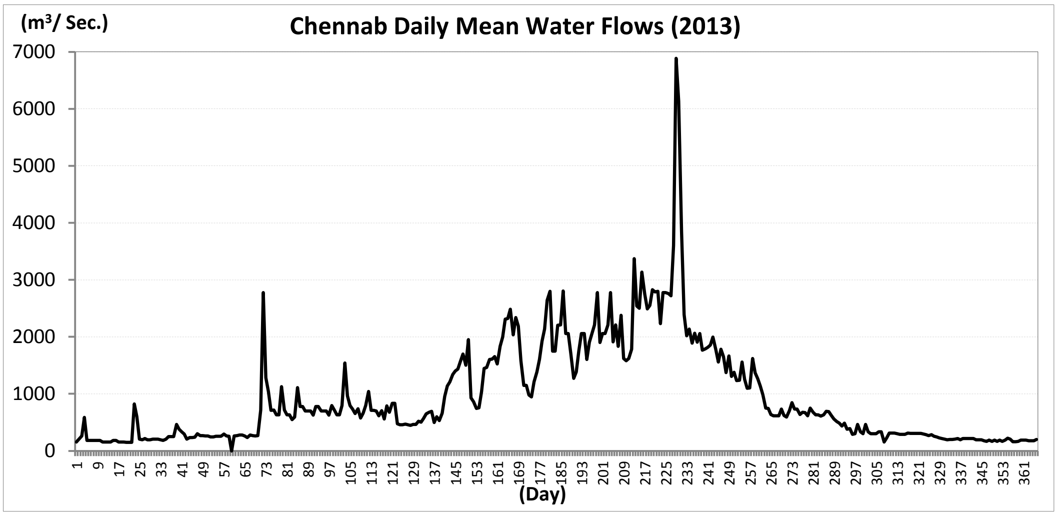

Figure 5. 3: Daily mean water flows in the Chenab River by 2013, at Marala, Pakistan
Source: (WAPDA, 2013, p. [Daily Reports])

Jhelum River

The Jhelum River is the second biggest river of Pakistan by power generation potential. It enters into Pakistan in the Azad Jammu & Kashmir (AJ&K) region. The river has a 1000 MW (Mangla) reservoir based hydropower plant (RHPP), and a limited potential of mini and micro run of river hydropower plant (RORHPP). The catchment area of the river receives regular rainfalls during the year, which contribute to a significant share in the flows (Yakub et al., 2015, p. 10). To observe the phenomenon, Figure 5. 4 presents the inflows recorded at the Mangla RHPP, Pakistan (PMD, [Daily], p. [Daily Reports]).

Indus River

The Indus River is the backbone of the Pakistan economy. It generates a major part of the hydropower and serves a significant share of the water demand. Of the total, the major share of the hydropower potential is along the river or its tributaries[78]. Compared to the Chenab River and Jhelum River, the Indus River flows reach a substantial level in summer. Consequently, the impact of monsoon rainfalls is relatively lessened (ADB, 2014), (ADB, 2010, p. 10). Since the melting of the glaciers and snow are more regular than the rainfalls, the flows of the river are more consistent (Figure 5. 5) (PMD, [Daily], p. [Reports]).

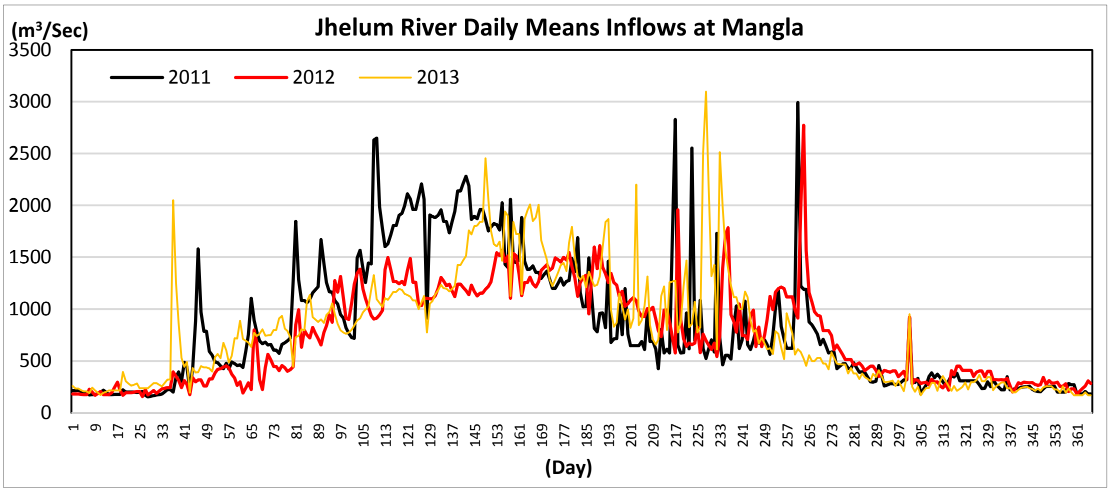

Figure 5. 4: Daily means water inflows in the Jhelum Rivers recorded at Mangla HPP, Pakistan
Source: (PMD, [n.d], p. [Daily Reports])

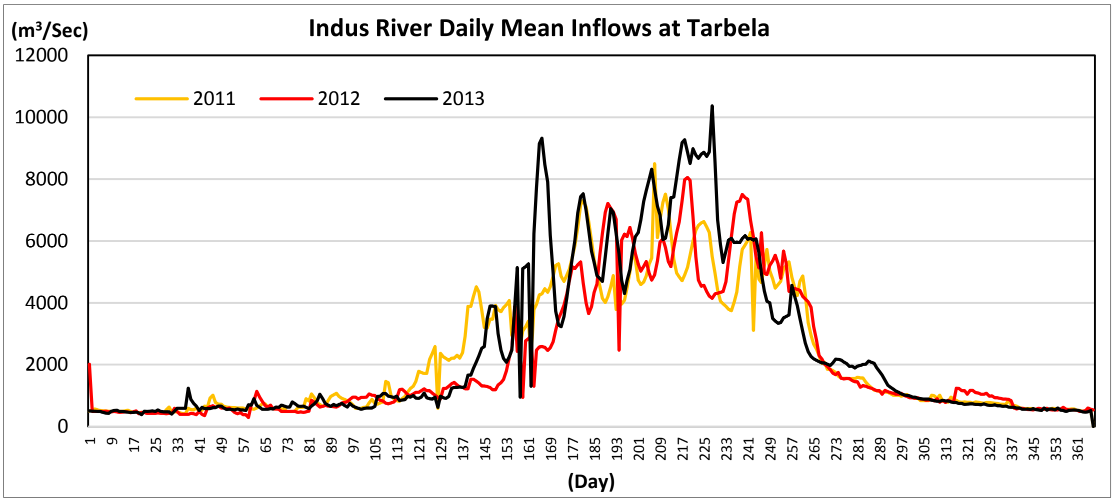

Figure 5. 5: Daily mean inflows in the Indus River recorded at Tarbela, Pakistan
Source: (PMD, [n.d], p. [Daily Reports]).

[78] Discussed in the later sections.

River Kabul

The River Kabul originates in the Hindukush mountain ranges, in Pakistan and Afghanistan. It passes through Afghanistan and enters into the northwest region of Pakistan. The country built its first RHPP (i.e., Warsak[79]) on the river, which has lost all the storage and more than 40% of the generation capacity (Rehman et. al., 2015, p. 1383). Except this project, there is no major potential site of power generation before its confluence with the Indus River. After merging with the Indus River, its water passes through several hydropower generation sites, including Chashma and Kalabagh. Its flow volume can be assessed from the flows shown in Figure 5. 6, recorded at Noshera, Pakistan (PMD, [Daily], p. [Daily Reports]).

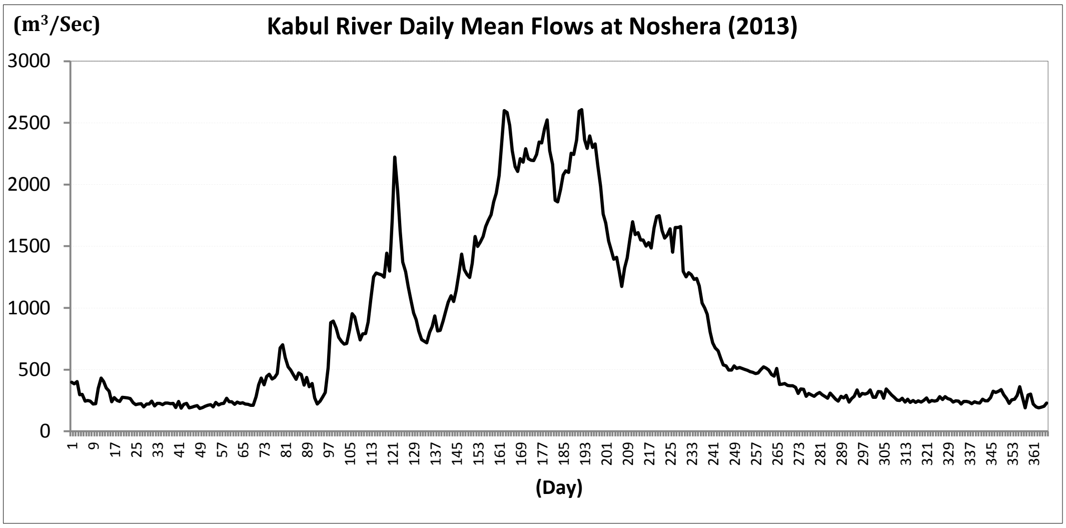

Figure 5. 6: Daily mean flows in River Kabul by 2013 recorded at Noshera, Pakistan
Source: (PMD, 2013, p. [Daily Reports])

5.1.5 Existing- Reservoir-Based Hydropower Plant (RHPP)

Reservoirs are important in regulating both power generation and water flow. Their role is more significant when the seasonal variations of Pakistan are considered. Currently, there are three major and one small RHPP in Pakistan, which are briefly discussed in the following section.

Warsak HPP

In 1960, the GOP built the first RHPP (i.e. Warsak) at the River Kabul, near Peshawar, KP[80]. At the time of the commissioning, the project had an electric capacity of 160 (40x4) MW and a gross water storage capacity of 31.237 million m^3 (WAPDA, n.d(f), p. [online]). During 1980-81, the GOP added a further 82.96 MWe, and the project total net capacity reached 240 MW (CIDA, 1999).

[79] Discussed later in the next section with detail
[80] Formerly, North West Frontier Province was rename as Khyber Pakhtunkhwa in 2010

Currently, the plant runs as a RORHPP due to the loss of the storage capacity by sedimentation. The plant has also lost some of its generation capacity due to components failure and/or efficiency reduction. Its current power generation capacity is around 160 MWe (Daily Tribune, 2011, p. [online]). For the flows of the river, the capacity is quite low and the plant annual capacity factor is between 70-80% (NTDC, 2010, p. 16; 2013).

In 1999, the Canadian International Development Agency (CIDA) conducted an evaluation of the project (CIDA, 1999). The study showed that the power generation capacities of the project can be restored (The News, 2012, p. [oline]). The initial environment examination (IEE) of the project is completed, and it is under appraisal for partial investment by the European Investment Bank (European Investment Bank, 2014, p. [online]). Regarding its water storage capacity recovery, no information was available.

Tarbela HPP

Tarbela HPP is the biggest RHPP of Pakistan and is located on the Indus River in the KP province. The construction of the project started in the late 1960s and was commissioned in the year 1976-77. At the time of commissioning, the reservoir gross storage capacity was 13.95 billion m^3 (BCM), which reduced to 11.11 BCM due to sedimentation (WAPDA, n.d(d), p. [online]). The initial power generation capacity of the project was just 700 MWe. However, a capacity of 1050 MWe was added during 1982-1985 and then, 1728 MWe during 1992-93, making the total 3478 MWe (NTDC, 2013, p. 1).

In summer, a significant volume of the water passes without power generation due to a relatively low storage capacity. To exploit the additional hydro energy, the GOP recently decided to install a further 1410 MWe on the site (GOP, 2012, p. 57). This will cost around 914 million US$, and the World Bank is appraising the project for investment (World Bank, 2012, p. 10).

Mangla HPP

Pakistan's second biggest RHPP (i.e., Mangla) is located on the Jhelum River near Mangla, AJ & K. The construction of the project was completed in 1967, and its gross storage capacity was 7.26 BCM at the time of commissioning (WAPDA, n.d(b), p. [online]). In more than 30 years, the reservoir has lost about 23% of its storage capacity (K.U.Chaudry & J.Akhtar, 2007, p. 04). To restore the capacity, the GOP initiated the "Mangla HPP Dam Raising Project" in 2004. The work was completed in 2012 and increased the reservoir storage capacity by 3.56 BCM (WAPDA, n.d(c), p. [online]). The current net water storage capacity of the Mangla reservoir is 5.77 BCM, and its annual capacity factor is in the range of 50% (Figure 5. 7) (NTDC, 2010, p. 16; 2013).

Chashma HPP

In 2001, the GOP constructed the Chashma HPP on the Indus River at the right abutment of the Chashma Barrage in Punjab province. The water storage capacity of the reservoir is around 0.3 BCM, with an installed power generation capacity of 184 MWe (WAPDA, [n.d], p. 01). Except the first two years, the generation performance of the Chashma HPP was remarkable, as shown in Figure 5. 7 (NTDC, 2010, p. 16; 2013).

5.2 Future Prospects

5.2.1 Hydro Power Development

Pakistan has a huge potential of hydropower generation[81], and the installed capacity is only 10-15% of the total (WAPDA, 2013a, pp. 3-4). In the past, only the GOP had the rights of HPPs development. However, the country changed the policy, and currently, private investors are also encouraged to invest towards the HPPs development. Furthermore, the provincial governments also have a mandate to promote and develop small or micro sized HPPs in their regions (Ministry of Water & Power, 2006, p. 2). Currently, seven big and thirteen medium to small size HPPs are under development in the country. In them, 4.5 GW Diamer Bhasha and 0.7 GW Munda are RHPPs (WAPDA, 2014, p. [online]).

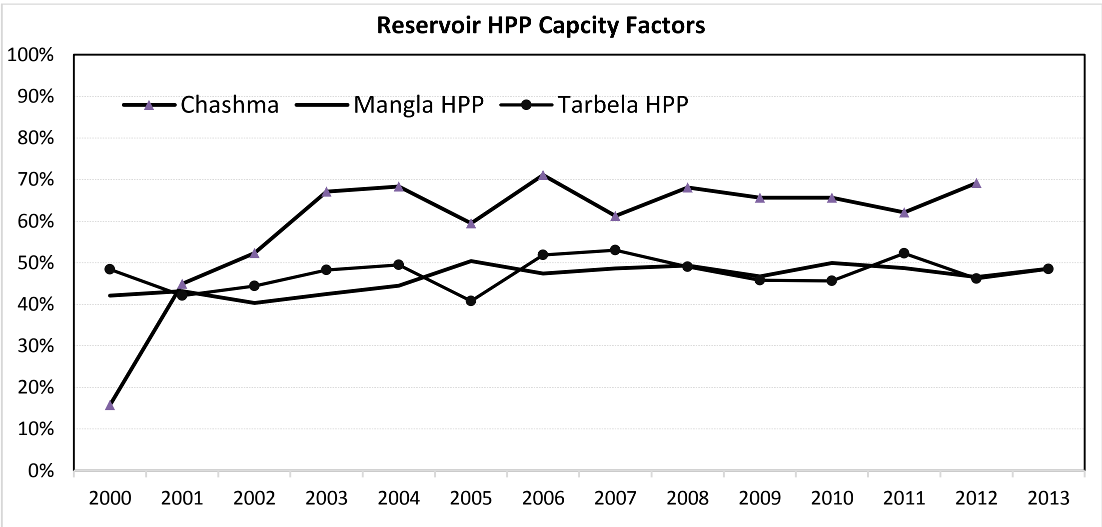

Figure 5. 7: Pakistan's existing RHPPs operational performance
Source: (NTDC, 2010, p. 16; 2013)

[81] More details are in the following sections.

5.2.2 Need of Hydro Reservoir in Pakistan

Pakistan critically needs to construct hydro reservoirs due to the important following three reasons.

Pakistan- A Water Stressed Country

Pakistan's water demand grew substantially due to population and economic growths. In the past, the GOP did little to exploit the resources and manage the demand. Consequently, the per capita availability of water has gradually decreased. Recently, the World Bank categorized Pakistan as a water stressed country (World Bank, 2005, p. 3).

Flood Control

A flood situation develops each year in the river system of Pakistan, and a frequent severe overflowing of the rivers has caused substantial destruction and damage. As an example, Figure 5. 8 shows the river flows at different points of IRS, during the summer of 2010, which resulted in a major flood (Federal Flood Commission, 2010, pp. 41-56). According to the World Bank, the flood caused a damage of 10.11 billion US$ to the national economy (ADB, 2010, p. 15).

During a flood situation, the authorities regulate the flows through the reservoir system (Tarbela, Mangla). However, the volume of the inflow water usually surpasses their storage capability (ADB, 2013, p. 7). Since the country's river system is interlinked, construction of a reservoir at any location can be helpful to scale down the intensity of the flooding across the system.

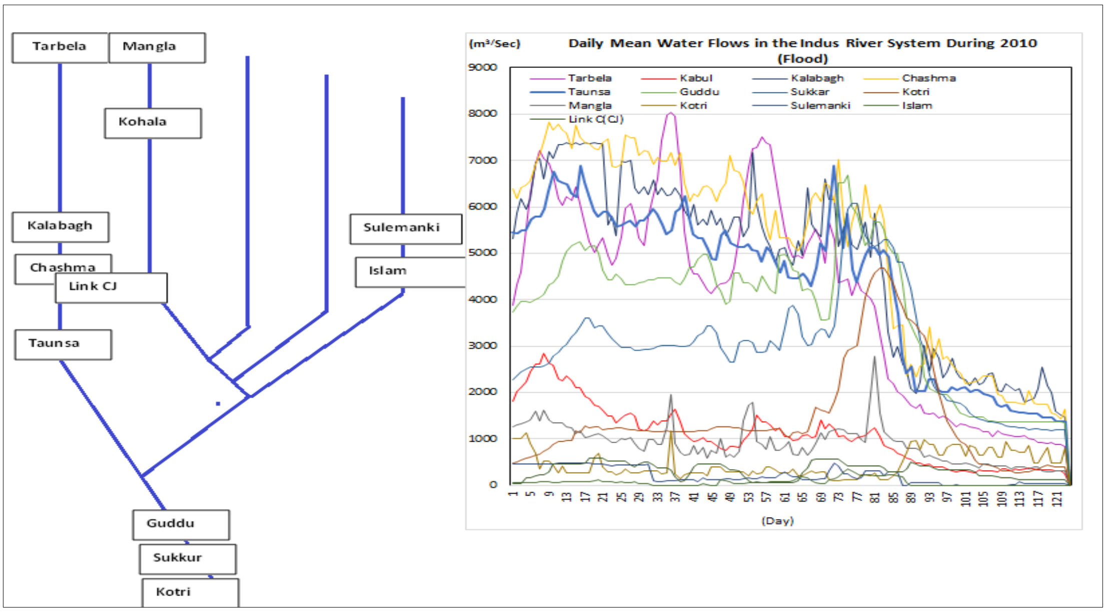

Figure 5. 8: Daily mean flows in IRS- Pakistan during July–September 2010 Flood
Source: (Federal Flood Commission, 2010, pp. 41-56).

Growing Energy Dependency

Pakistan imports energy in the form of oil for power generation, which results in high generation costs. In a low income country like Pakistan, it is hard for the consumers to pay for such high energy prices[82], particularly when the international energy prices are high. To overcome the issue, the system frequently needs the financial support of the government (Aziz & Ahmad, 2015, pp. 2-3). An increase of indigenous hydropower generation can help the system to operate at a low cost. The development will also help the country to save its foreign reserves.

5.3 Hydropower Potential

Pakistan's hydropower potential is in the range of 55-60 GW, including installed, under construction, under development, identified etc., projects. In total, more than 90% of the potential is in the northern areas of the country. At a glimpse, Figure 5. 9 shows the major installed, under construction and under development projects in the region (PPIB, 2011, p. 08). In this thesis, most of the potential has been considered, while analyzing the demand-supply balance of the country. For the sites that don't have reliable information about their heads, a capacity factor of 45-50% is assumed as the value has been used in a recent study for the country (IAEA, 2011, p. [para. 1.2.1]).

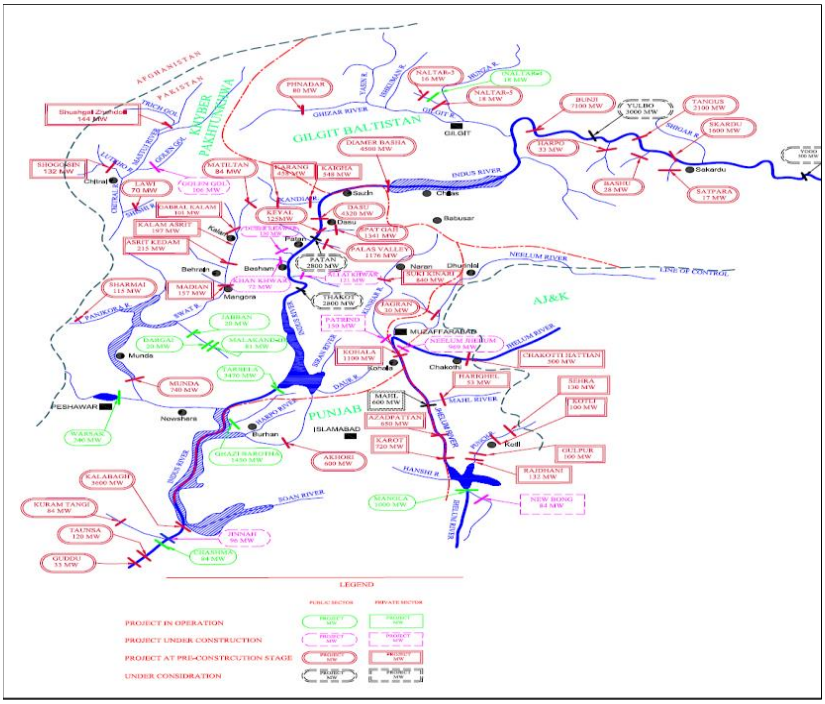

Figure 5. 9: Map of Pakistan's major hydropower projects
Source: (PPIB, 2011, p. 08)

[82] More than 50% installed capacity in Pakistan uses oil for power production. It is discussed in details in the chapter 08 of the thesis.

5.3.1 Reservoirs based Hydropower Potential

Pakistan's known potential of RHPP is around 13.5 GW, having a storage capacity of 31.6 BCM. According to their physical location, TABLE 5. I contain the distribution potential at a regional level (PPIB, 2011, pp. 9-87).

TABLE 5. I: Pakistan existing and identified RHPP potential (PPIB, 2011, pp. 9-87)

Region	Project	Live Storage (BCM)	Power Potential (MW)	Status by 2013
KP – 1	Tarbela HPP	8.5	3478	Existing
KP – 1	Munda HPP	0.8	740	Under Const.
Gilgit	Diamer B. HPP	7.9	4500	Under Const.
FESCO	Kalabagh HPP	7.5	3600	Planned
FESCO	Chashma HPP	0.3	184	Existing
AJ & K	Mangla	6.6	1000	Existing

5.3.2 Pump Hydroelectric Storage (PHES) System

PHES systems are mostly used in developed countries in load management of a power system. The advent of wind and solar resources in the supply mix of power systems has increased their importance. In general, it is the most attractive storage option due to its low cost, high storage capacity, proven technologies and quick response time. However, the problem is its scarcity and geographic dependency (Euroelectric, 2015, pp. 6,10).

Pakistan currently has no PHES facility, and the GOP has not initiated any effort to investigate the potential. One possible reason for this could be the availability of abundant hydropower generation sites. However, the GOP has planned to build a 200 MW Dotara Dam PHES facility on the Haro River[83] for demand management (WAPDA, 2013a, p. 58). The site is in IESCO region and in a relatively flat area. The initiative of the project, therefore, indicates some high prospects of the resources in the regions like, Gilgit Baltistan (GB), KP, AJ&K, Baluchistan and FATA.

Recently, Hall & Lee (2014, pp. 08,34) assessed the potential of PHES capacity in the USA. He has used two general criteria, among others, to identify the sites. The first criterion is the availability of water bodies, while the second is the proximity of potential sites (i.e., water bodies). Having no information, the two criteria helped in the estimation of PHES potential in Pakistan as follows.

There are dozens of lakes and water bodies in the northern and northwestern parts of Pakistan, as shown in Figure 5. 10 (Pakistan Wetland GIS, [n.d], p. [online]). From the map, it is clear that the sites are in the areas of the existing and potential sites of hydropower. This means that the grid system will expand in the region to transmit the generations. The proximity of the sites is, therefore, suitable for the development of PHES systems in the areas.

[83] Haro is a seasonal river and is almost dead in winter

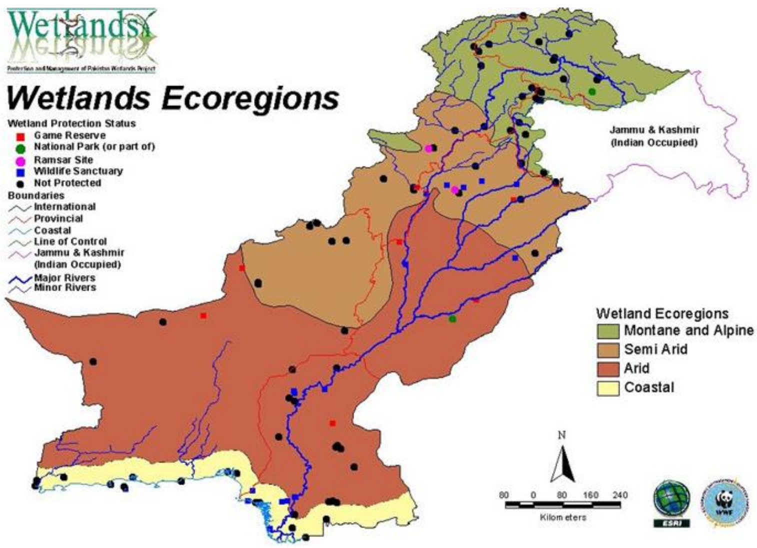

Figure 5. 10: Water bodies and lakes in Pakistan
Source: (Pakistan Wetland GIS, [n.d], p. [online])

Hall & Lee (Hall & Lee, 2014, p. 08) used an online GIS approach to identify the potential sites for PHES projects. Following the same approach, the potential of the 24 sites in Pakistan has been estimated. The online services; Google Map ([n.d(a)], p. [online]), Altitude Calculator ([n.d], p. [online]) etc., helped in an estimation of the water bodies areas and site heads. The volumes of the water bodies are unknown; therefore, the two values of the depth (10m, 20m) were assumed for the analysis. Appendix-B has the details of the work, while TABLE 5. II present the total potential assessment, based on the 24 sites.

Although the potential assessment is based on the online observations and the actual value can differ. Still, the number of water bodies (i.e. sites) is higher than considered and the actual potential can be much more. Furthermore, to use a conservative approach, the values used in the analysis of the demand-supply balance were relatively low (i.e., 4.4-7.9 GW and 7.8-14.0 GW in the OG_Demand_Scenario and HG_Demand_Scenario respectively).

TABLE 5. II: Regional PHES potential in Pakistan (Estimates)

Region	**No. of Water Bodies**	**Potential (MW)**	
		(10 m depth)	*(20 m depth)*
AJ&K	05	512	1,280
Gilgit	07	5,680	13,864
KP - 1	07	5,823	14,5558
FATA	02	586	1466
Baluch. – 4	03	454	1,137
Total	**24**	**13,057**	**32,306**

5.3.3 Total Generation Potential

For analysis, the installed and prospective resources[84] of the HPPs have been considered. The generation potential was distributed among the regions according to the projects physical location. In TABLE 5. III, a summary of the potential at regional level is presented (PPIB, 2011, pp. 9-87)[85].

TABLE 5. III: Total assessed hydropower potential at regional level (PPIB, 2011, pp. 9-87)

Sr. No;	Region	Hydro Potential (MW)
1	AJ & K	5,400
2	Gilgit	19,385
3	FATA	95
4	KP - 1	22250
5	LESCO	56
6	GEPCO	1295
7	FESCO	5810
8	MEPCO	21
9	SEPCO	193
	Total	**54,453**

5.4 Hydro Resources as a Seasonal Storage Option:

As mentioned before, 80% of the total water passes through Pakistan's river system in a short period of time (GOP, 2010, p. 14). Consequently, significant shares of the flows escape to the Arabian Sea without utilization. The historical data shows that the runoff annual average value of the last 25 years is in the range of 43-47 BCM (Sharif, [n.d], pp. 3,9). This means that an average of approximately 11-16 BCM water will be available after the development of the planned storages. Using the water, a substantial amount of energy can be generated, even without the installed capacity of the power generation on the storage(s). The value of the energy is estimated to be between 4-14 TWh if the water is used only by the three RHPPs of the Indus River (TABLE 5. IV). In the table, the two values are based on an assuming average and estimation of the dead levels of the reservoirs. In practice, the generation will be much higher when the water passes through the existing and prospective RORHPPs. Moreover, the flood control and availability of water for other purposes will be the additional benefits of the storage system.

TABLE 5. IV: Potential electricity generations from extra water, when used by the three RHPP (Assessment)

Storage Location (s)	Total Energy (TWh)	
	Avg. Level Head of HPPs	*Dead Level Head of HPPs*
1. Upstream of Ghazi Barotha HPP	13.85	10.21
2. Between Tarbela and Ghazi Barotha HPPs	8.03	6.33
3. Between Kalabagh and Tarbela HPPs	4.07	3.73

[84] Potential resources included all identified resources of the type major, medium, small, and micro hydro projects.

[85] The total of the resources is slightly lower than the one mentioned in Chapter 01, due to exclusion of the solicited micro projects. There was limited information about the project location.

5.5 Chapter Summary

The river system of Pakistan consists of six major rivers, and is called the Indus River System (IRS) basin. A melting of the northern glaciers[86] and winter snowfalls with regular rainfalls, charge the system. Consequently, about 80% of the water passes through the IRS during summer. These high flows frequently causes flooding. In contrast, the country is water stressed during winter. In this scenario, a development of further reservoirs is a convincing option.

The country has a known hydropower potential of around 55-60 GW, including 14.1 GW reservoirs based hydropower plant (RHPP). However, the existing capacity is only about 10-15% of the total potential. Currently, several hydropower projects are under development, including; the 4.5 GW Diamer Bhasha and the 0.7 GW Munda RHPPs. There are also dozens of natural water bodies in the country, which provide opportunities for the development of the PHES systems.

[86] Glaciers of the Himalaya, Hindukush and Karakorum

Chapter 06: Pakistan's Solar Resources

The sun radiates substantial energy, but the availability and daily pattern of the radiations are not similar around the globe. Generally, locations near the equator are more attractive in utilizing solar resources due to two factors. First, the concentration of the radiations increases on the earth's surface by getting closer to the equator (Lynn, 2010, pp. 6-10). Second, the seasonal variations in the availability of the resources are lessened near to the equator, when to compared to the Polar Regions (MIT, 2015, p. 263). Beside these two factors, regional weather and geographic conditions are also critical for the exploitation of the resources.

Pakistan is relatively closer to the equator, but the geographic and weather conditions vary across the country. Consequently, the resources availability changes both temporally and spatially. Still, most of the areas receive good radiations throughout the year. This chapter describes the resources potential and availability in Pakistan. Furthermore, a model used for generating hourly profiles of the solar insolations is also explained. The profiles were required in order to assess the hourly generation of the PV potential resources in Pakistan. However, before these details, there is a brief description of the resources development in the following section of the chapter.

6.1 Solar (PV) Resources Development in Pakistan

6.1.1 Development Activities

During the 1980s, the GOP installed eighteen (18) PV systems of a total 440 kW capacity, for experimentation and resource assessment (AEDB, 2005, p. 10). Currently, the technology is being installed at all levels, from a private home to grid-connected projects. In these activities, the well-known projects are briefly described below.

6.1.1.1 Grid Connected Projects

Japan International Cooperation Agency (JICA) Projects

JICA initiated two PV projects in the capital city (i.e., Islamabad) of Pakistan, having a total capacity of 356.18 kW. The locations of the projects are in the premises of the Planning Commission of Pakistan and Pakistan Engineering Council buildings. Each of the two projects has a capacity of 178.1 kW (NEPRA, 2014, p. 8). In March 2012, the projects were completed with a total cost of 960 million Japanese Yen and connected to the national grid (JICA, [n.d], p. [online]).

Pakistan Parliament House Project

In 2014, the Chinese' government announced one (01) MW PV project for the Parliament House of Pakistan. The project cost was assessed to be around 2.33 million US$. (NA Sectt., 2015, p. [n.p]). According to media reports, the project is developed on the rooftop of the building and was recently inaugurated (Daily Times, 2016, p. [online]).

Quaid-e-Azam Solar Power Project

In 2014, the provincial government of Punjab province initiated a 1000 MW PV based power generation facility (The Daily Tribune, 2014, p. [online]). On May 5, 2015, the first phase of the project was completed. The installed capacity of the phase is 100 MW, and development of the next phase is in progress (QA Solar, [n.d], p. [online]).

Projects with Letter of Interest

In addition to the above projects, the GOP has issued a "Letter of Interest" to 24 other projects (TABLE 6. I). The total capacity of these projects is 793 MW (AEDB, [n.d(b)], p. [online]).

TABLE 6. I: PV electricity generation projects in Pakistan with LOI (AEDB, [n.d(b)], p. [online])

S.No	Company	Capacity (MW)	Province
1	First Solar	2	Punjab
2	DACC Associates	50	Punjab
3	Access Solar (Pvt) Ltd	10	Punjab
4	Associated Technologies Pvt Ltd	30	Punjab
5	Bukhsh Energy Pvt Ltd	10	Punjab
6	Avelar Energy Group	50	Punjab
7	Wah Industries Ltd	5	Punjab
8	Solargen Pvt Ltd	50	Punjab
9	Hecate Energy	50	Punjab
10	Hecate Energy	150	Punjab
11	Trans Tech Pakistan	50	Punjab
12	Sunlux Energy Innovations	5	Punjab
13	Sapphire Solar Pvt Ltd	10	Sindh
14	Realforce Ruba Pakistan Power Pvt Ltd	20	Punjab
15	Global Strategies (Pvt) Ltd	10	Punjab
16	Forte Pakistan	0.99	Punjab
17	Integratted Power Solution (Pvt) Ltd	50	Sindh
18	Jafri & Associates	50	Sindh
19	solar Blue Pvt Ltd	10	Sindh
20	Zaheer Khan & Brothers	10	Punjab
21	Dawood Group Ltd	10	Sindh
22	Table Rock Associate	100	Punjab
23	Safe Solar Power Pvt Ltd	10	Punjab
24	Techaccess FZ LLC II	10	Punjab
	Total	**792.99**	

6.1.2 Off-grid Capacity

Currently, there is limited information pertaining to the off-grid PV installations in Pakistan. The GOP, however, published the records of the PV imports, as shown in Figure 6. 1 (Ministry of Finance, 2014, p. 200). Having almost no information, the records are good indicators for an assessment of the off-grid PV installation activities in the country. The figures clearly show that the imports grew rapidly in the last few years, and one can expect that the present off-grid capacity is more than 100 MW.

6.1.3 Feed-in Tariff for PV Projects

The GOP proposes the upfront tariffs for the new PV projects, from time to time. The current upfront tariffs for a project in the northern areas of the country are in the range of 14.75-15.027US$ cents/kWh and 14.156-14.41 US$ cents/kWh in the southern parts (NEPRA, 2014, p. 42). Compared to a fossil fuel based generation, the offered tariffs for PV projects are significantly higher (NEPRA, 2014a, pp. 31-33).

6.2 Solar Resources

According to the NREL (2006, p. [database]), the annual daily means of the global insolation[87] on a flat tilted surface in Pakistan are in the range of 4.0-7.5 kWh/m^2/day. To assess the spatial distribution of the resource, Figure 6. 2 presents the insolation map of the country. The map shows that the values are significantly high in most parts of the country.

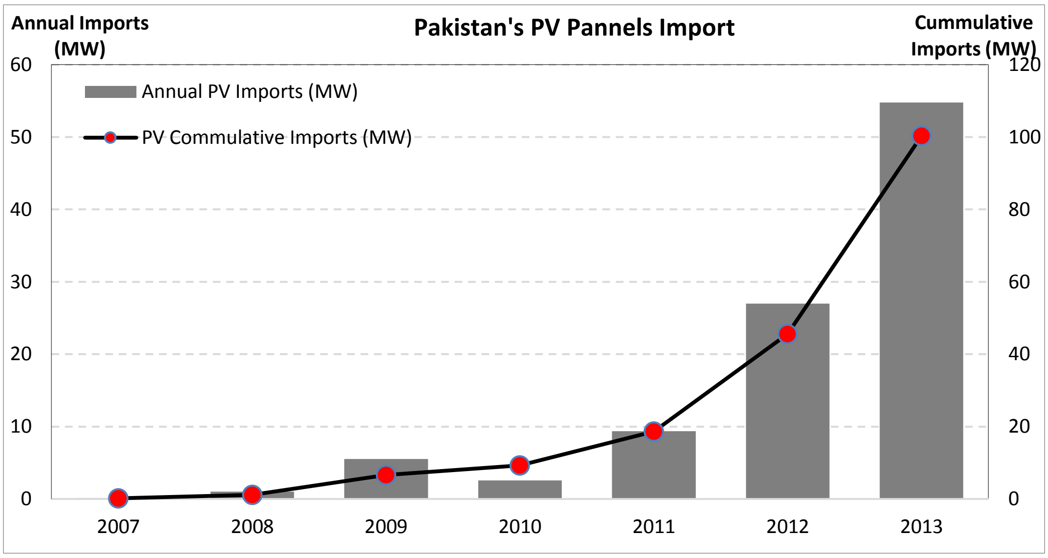

Figure 6. 1: PV panels import by Pakistan
Source: (Ministry of Finance, 2014, p. 200)

[87] Generally, the terms "irradiance" and "insolation" are used interchangeably, However, according (Sandia, [n.d], p. [online]), irradiance is relevant to instant power generation, while insolation (period mean value) is used for cumulative energy in a specified energy.

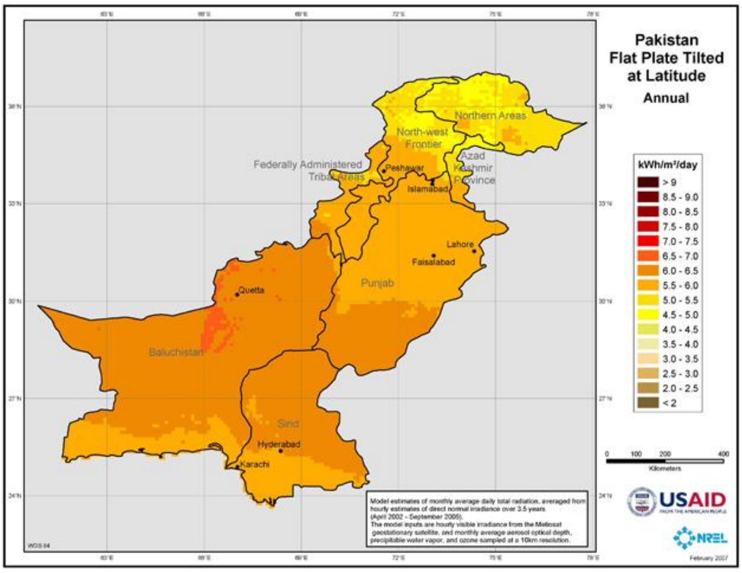

Figure 6. 2: Pakistan annual daily mean solar map
Source: (ASDC, 2013, p. [online]), (NREL, [n.d]b, p. [online])

6.3 Monthly Daily Mean Insolation

In Figure 6. 3, the monthly daily mean global insolation of different regions[88] is shown (ASDC, 2013(b), p. [online]). Compared to the annual values, they are more informative in assessing the seasonal and spatial variations in the resources. The figure shows that the winter insolations are lower than the summer, almost everywhere in the country. However, during the period, the southern parts (i.e., red and green curves) receive reasonable insolations. In contrast, the mean values in the remaining country are relatively better than the areas during summer.

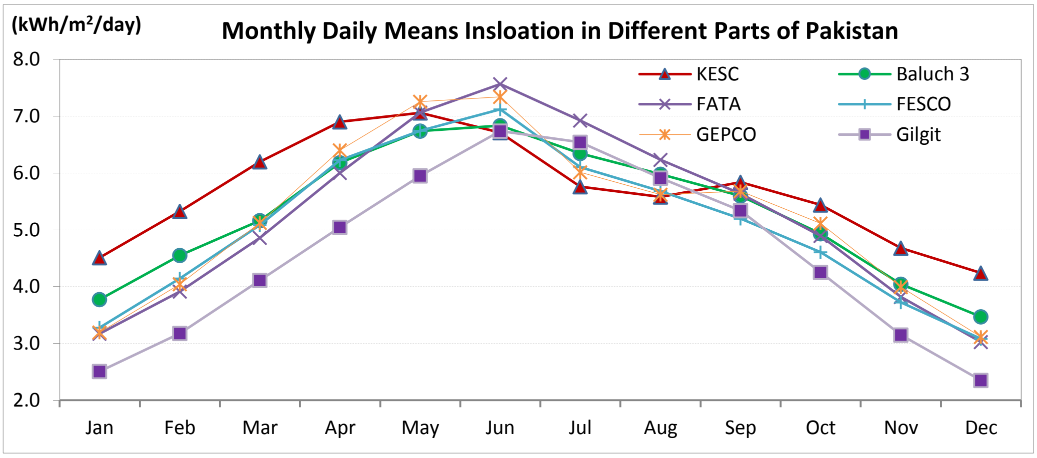

Figure 6. 3: Pakistan's monthly daily mean global Insolation in different parts of the country
Source: (ASDC, 2013, p. [online]).

[88] KESC & Baluch 3 represent southern, GEPCO & FESCO central while FATA & Gilgit represent northern Pakistan

6.4 Solar Insolation Data

The research required a high temporal and spatial resolution set of data, concerning the solar insolation. Due to limitations of the data availability from local sources, the published datasets of NASA were used in the research. Details of which are given in the following section.

6.4.1 NASA's Solar Insolation Datasets

NASA has uploaded the "Surface Meteorology and Solar Energy Release 6.0" datasets. The datasets are prepared from satellite data and provide information of the resources availability around the globe. For improvements, the satellite data are treated with modeling tools to incorporate the effects of factors like aerosols, diffusion, etc. For guidance, NASA has provided the description and details of the datasets preparation, from which, a few important points are summarized below (ASDC, 2013(b), p. [summary]).

- Most of the datasets are equipped with a space resolution of 1^o latitude x 1^o longitude. However, some information (e.g., daily mean insolation) can be found for a specific location.
- The datasets are prepared for the analysis of a PV system and available in different time resolution, i.e., yearly, monthly, daily, etc.
- In addition to the insolation data, there is also information of the other relevant parameters, e.g., cloud density, temperature, etc.
- During preparation, the bias of the data has been minimized and maintained a negative value (i.e. -1.58 to -2.24). The negative values ensured that the solar insolation assessed from the datasets would be lower than the actual. However, the impact of local air pollutions is not incorporated within the insolation values.

6.5 Solar Insolation Hourly Profiles

The hourly profiles of the insolation in different regions of Pakistan (Appendix-C) were prepared using the following datasets of NASA (ASDC, 2013(b), p. [online]).

- Daily mean available horizontal surface global insolation (AHGI)
- Daily mean maximum horizontal surface global insolation (MHGI) under clear sky conditions
- Monthly mean daytime cloud cover, with a 3-hour interval (at 3:00,11:00,14:00,19:00 GMT)

Using the datasets, the patterns were generated as follows.

Daily Blocked Insolation

From AGHI and MGHI values, the blocked daily mean for a horizontal surface global insolation (BGHI) was found through their difference i.e.,

$$BHGI = MHGI - AHGI$$

Clear Sky and Available Hourly Insolation

The daily mean values of AHGI and MHGI were distributed into hourly mean values. For the distribution, the Liu and Jordan model of hourly to daily ratio was used. In eq. 6.1, a mathematical form of the model can be seen (Khatib & Elmenreich, 2015, pp. 2-3).

$$AHGI_h = AHGI_D * \pi/_{24} * \frac{cos\ \omega - cos\omega_s}{sin\omega_s - (2\pi\omega_s/360)cos\omega_s} \dots\dots\dots\dots\dots\dots\dots..\dots eq. 6.1$$

Where $AHGI_D$ is the daily mean value of a day "D", while $AHGI_h$ is the hourly mean value in hour "h" of the day. In the equation, ω is the hourly value of the sun angular displacement from the location of interest. The value of which can be found as follows (Khatib & Elmenreich, 2015, pp. 2-3).

$$\omega = 15(LST + EoT + 4(LSMT - LON) - 12) \dots.\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots. eq. 6.2$$

In the relationship, LST is the local standard time, LON is the longitude of the location, $LSMT$ represents the local standard meridian, while EoT is the equation of time. $LSMT$ for a location can be determined by using eq. 6.3 (Khatib & Elmenreich, 2015, pp. 2-3).

$$LSTM = 15 * Rounded\ (LON/15) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.\dots.. eq. 6.3$$

The EoT value can be determined on a given day "D" as follows:

$$EoT = 9.87 \sin\Big(2\big(0.986(D - 81)\big)\Big) - 7.53 \cos\big(0.986(D - 81)\big) - 1.5 \sin\big(0.986(D - 81)\big) \dots\dots\dots\dots\dots\dots\dots\dots\dots \dots...\dots\dots. (eq. 6.4)$$

The value of a sunset hour angle (ω_s) on a day "D" for a location with latitude "LAT" can be found, using the following trigonometric relationship (Khatib & Elmenreich, 2015, pp. 2-3).

$$\omega_s = \cos^{-1}\left(-\tan(LAT) * \tan\left(23.45 \sin\left(\frac{360(284 + D)}{365}\right)\right)\right) \dots\dots\dots\dots\dots.\dots.. eq. 6.5$$

Using the model, the hourly to the daily insolation ratio profile of IESCO region is given in Figure 6. 4.

Daytime Cloud Cover Hourly Profile

The daily values of BHGI were distributed across daytime using the datasets of cloud cover intensity. In the dataset, the hourly missing values between two given data points were approximated using interpolation. For extreme hours, a relationship was derived using the given data of each month. As a sample, Figure 6. 5 shows the mean values of the cloud cover intensity during January, in the MEPCO region.

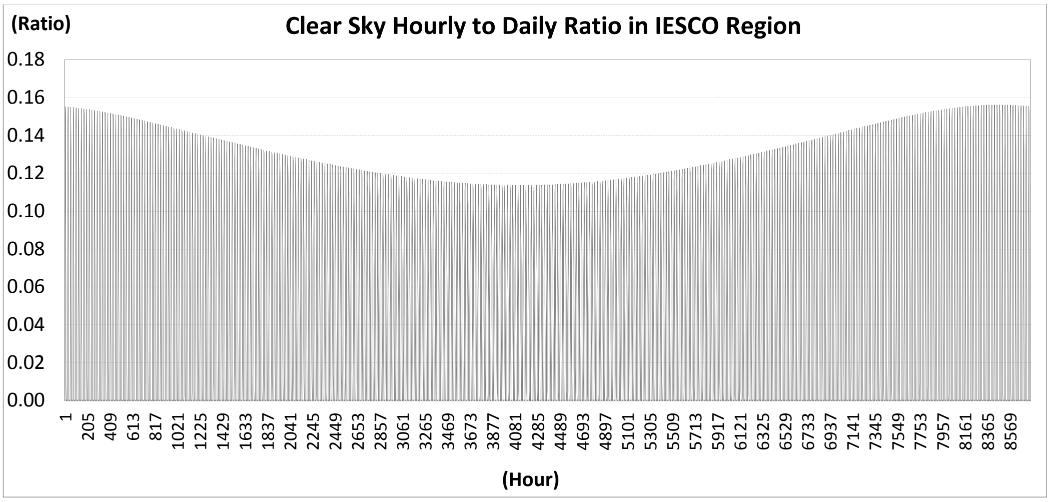

Figure 6. 4: Hourly to daily ratio of solar insolation in IESCO region, Pakistan (Derived)

Hourly Blocked Insolation

As a general observation, cloud blocks more radiation at a time of higher insolation i.e., the blocked radiations at noon are higher than morning for the same amount of cloud cover. This impact is incorporated into the hourly values, by using the following weighted parameter.

$$IWCC_D = \sum_{H=1}^{24} (MHGI_H * CC_H) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots eq. 6.6$$

$$BHGI_H = BHGI_D * \frac{(MHGI_H * CC_H)}{IWCC_D} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots eq. 6.7$$

In the equations,

$IWCC_D = Sum\ of\ insolation\ weighted\ cloud\ cover\ of\ day\ "D"$

$MHGI_H = \ Maximum\ GHI\ in\ hour\ "H"$

$BHGI_H = \ Blocked\ GHI\ in\ hour\ "H"$

$CC_H = \ Cloud\ cover\ in\ hour\ "H"$

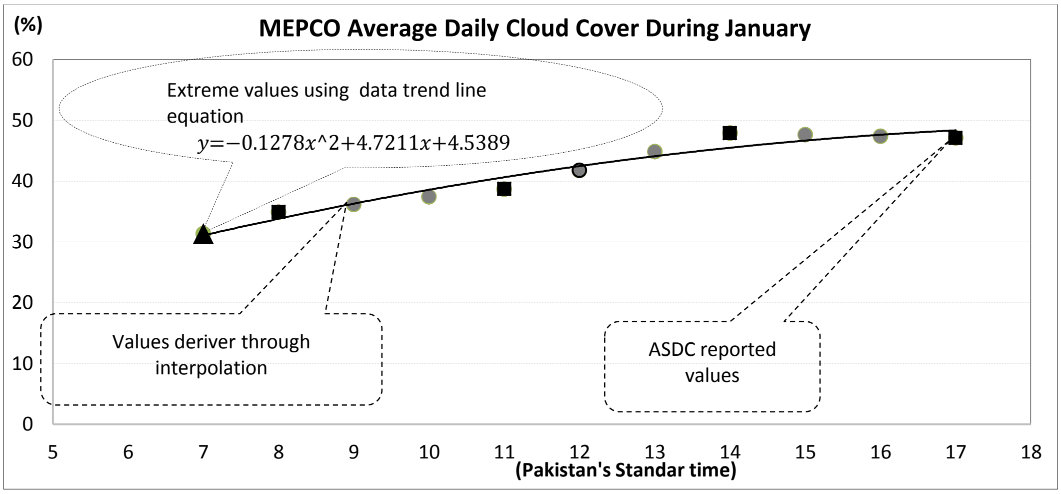

Figure 6. 5: Daily mean hourly cloud cover during daytime in MEPCO region Source: (ASDC, 2013, p. [online])

Synthetically Generated Hourly Data

The values of the desired hourly profile were obtained by subtracting hourly values of the BHGI from MHGI, as shown below. In the equation "H" represents an hour with values 1 to 8760.

$$GHI_H = MGHI_H - BGHI_H \ \ldots\ldots\ldots\ldots\ldots.. eq. 6.8$$

As an example, Figure 6. 6 shows the generated hourly values of the hourly mean solar insolation in the IESCO region.

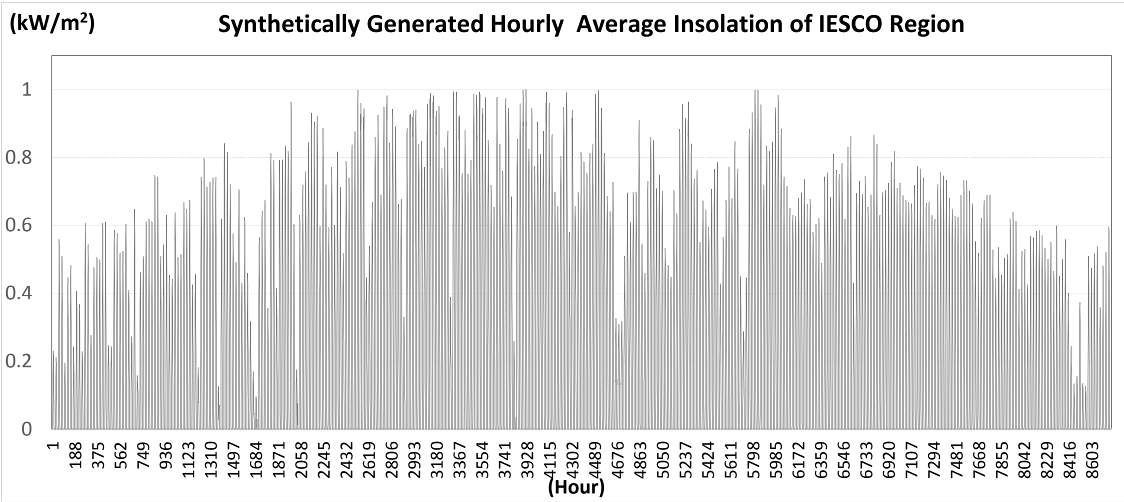

Figure 6. 6: Hourly mean solar insolation in IESCO region
Synthetically generated using information (ASDC, 2013(b), p. [online])

6.6 PV Potential

The PV potential of Pakistan is mapped out by the NREL, USA, in a toolkit at a regional level (NREL, 2006, p. [database]). Using the toolkit while applying the following land-use constraints, the estimated potentials in different regions of the research are given in TABLE 6. II.

- Included: I). Urban and built-up land
- II). Barren or sparsely vegetated (excluding the protected area)

At this point, it is important to mention that the potential shown is only for information (i.e., indicative). During research, in most regions, the assessed PV capacities are only a fraction of the values.

TABLE 6. II: Indicative regional potential of PV in Pakistan

Region	Potential (GW)
KESC	41.6
Baluch 1	1864.5
Baluch 2	1864.5
Baluch 3	3729.0
Baluch 4	1864.5
HESCO	332.5
SEPCO	457.1
MEPCO	213.1
FESCO	79.9
LESCO	79.9
GEPCO	79.9
IESCO	79.9
FATA	29.5
KP 1	157.4
KP 2	52.5
AJK	11.2
Gilgit	589.5
Total	**11526.6**

6.7 Chapter Summary

Pakistan's solar resources are good to excellent, due to closeness to the equator. In the country, the annual daily means from insolations on a tilted flat surface are up to 7.5 $kWh/m^2/day$. However, the geographic diversity of the country affects the availability of the insolation, particularly in the north.

In this research, NASA's datasets of insolations and cloud cover were used, due to limitations of the data availability in Pakistan. The daily mean insolation data of the datasets were transformed to hourly mean values, using the Liu and Jordan model. Regarding the potential of PV capacity, conditions in the country are encouraging. According to the NREL, the potential of the country is around 10-12 TW after applying land utilization constraints.

Chapter 07: Pakistan's Wind Resources

7.1 Introduction

Pakistan's wind resources can be categorized as average or above average, both by quality and potential, based on available information. However, the resources can play an important role in the development of a renewable resource based electric supply system in the country. This chapter describes the recent status of the resources ongoing development in the country. The description includes the details of installation as well as the exploration efforts. In later sections, the chapter presents the wind speed profile of prominent sites and regional potentials of the resources, considered in the research.

7.2 Wind Resources Development in Pakistan

7.2.1 Government Incentives

In 2006, the GOP announced a short-term renewable energy policy. The policy objective was to use the experience in the formulation of a long-term policy to promote the resources[89]. According to the policy, the government bore the risks associated with the energy generation of a wind power project in case of the resources unavailability, provided the project was technically available (Ministry of Water & Power, 2006). Furthermore, the GOP offered high enough tariffs to encourage wind power projects in the country. For example, the upfront tariff for a wind power project was 13-14 US$ cents/kWh in 2011 (NEPRA, 2011, p. 8), while for a coal project, the offer was 8.50-9.56 US$ cents/kWh even in 2014 (NEPRA, 2014a, pp. 31-33).

7.2.2 Installed Capacity

Currently, Jhimpir site is the most active site regarding the development of the projects. It is 114 km from the country's major metropolitan center, Karachi and has the following two operational wind power projects.

FFCEL Project

FFCEL[90] wind power farm in Jhimpir is the country's first wind project. The installed capacity of the project is 49.5 MW and has 33 wind turbines. Its development started in 2011 and was completed by the end of 2012. The project's total cost was 134 million US$, and its annual generation is approximately 145 GWh. The GOP awarded a levelized tariff of 16.1 US$ cents/kWh to the project (FFCEL, 2013, p. [online]).

[89] The policy is already discussed in details in the earlier chapters.
[90] FFCEL invested in several kind of projects, it was, therefore, necessary to specify the wind farm of the company.

Zorlu Enerji Pakistan Ltd., (ZEPL) Project

Zorlu Enerji Pakistan Ltd[91]., developed a 56.4 MWe wind power project at the Jhimpir site. For the project, Vestas 1.8 MW (i.e., V90) wind turbines have been used, and the total cost was about 161.88 million US$ (ZEP Ltd., 2013, p. [online]). The project was completed by December 2012 and received a levelized tariff of 15.01 US$ cents/kWh for a period of 20 years (NEPRA, 2012, p. 22).

7.2.3 Under-Development Projects

In addition to the Jhimpir site, the Gharo site in the Sindh province is also active in terms of development. In the following section, details of the prospective projects at the two sites are briefly described.

Tariffs Awarded Projects

NEPRA has evaluated the petitions of six projects and awarded them tariffs, details of which are presented in TABLE 7. I (AEDB, [n.d(a)], p. [online]).

TABLE 7. I: Wind power projects with a status of "Tariffs Awarded Projects" (AEDB, [n.d(a)], p. [online])

Company Name	Tariff (US$ Cents per kWh)	Site/ Location	Capacity (MW)	Announcement Date of Tariff
Three Gorges Wind Farm Pakistan	13.9399	Jhimpir	50	15-Dec-11
Metro Power Company (Pvt.) Ltd.	14.4236	Jhimpir	50	15-May-12
Foundation Wind Energy I (Pvt.) Ltd.	14.1359	Kuttinkun (Gharo)	50	16-Mar-12
Foundation Wind Energy II (Pvt.) Ltd.	14.1164	Kuttinkun (Gharo)	50	16-Mar-12
Sachal Energy Development (Pvt.) Ltd.	15.8618	Jhimpir	50	13-Jan-14
Zephyr Power (Pvt.) Ltd.	15.9135	Bhambore (Gharo)	50	24-May-12

On October 6th, 2011, NEPRA has announced new upfront tariffs for wind power projects and presented 14.6628 US$ cents/kWh for a period of twenty years (NEPRA, 2011, p. 8). Several firms (TABLE 7. II) have accepted the offer and have received the general license of the projects development (AEDB, [n.d(a)], p. [online]).

Land Allocated Projects

The GOP has allocated land to a few projects, which are in the early phase of development. Among them, the known projects are Abbas Steel I & II, CWE, Arabian Sea Wind Energy (Pvt.) Ltd., HOM Energy (Pvt.,) Ltd., Dawood Power Ltd., New Park Energy (Pvt.) Ltd., etc.

[91] Zorlu Enerji Pakistan Ltd has been established by the Zorlu Group, a Turkish Corporation

TABLE 7. II: Wind projects with a status of "Upfront Tariffs Awarded Projects" (AEDB, [n.d(a)], p. [Online])

S. No:	Company Name	Site/ Location	Capacity (MW)
1	Yunus Energy Ltd	Jhimpir	50
2	Sapphire Wind Power Company Ltd.	Jhimpir	50
3	Tapal Wind Power Company Ltd.	Kuttinkun (Gharo)	-
4	UEP Wind Power (Pvt.) Ltd.	Kuttinkun (Gharo)	100
5	Master Wind Energy Ltd.	Jhimpir	50
6	Gul Ahmad Wind Power Ltd.	Bhambore (Gharo)	50
7	Finerji (Pvt.) Ltd.	Jhimpir	-
8	Hawa Energy Ltd.	Jhimpir	-
9	Dewan Energy (Pvt.) Ltd.	Jhimpir	-
10	China Sunec Energy (Pvt.) Ltd.	Jhimpir	50
11	Titan Energy Pakistan (Pvt.) Ltd.	Jhimpir	-
12	Tenaga Generasi Ltd.	Kuttinkun (Gharo)	50
13	Hydro China Dawood Power (Pvt.) Ltd.	Bhambore (Gharo)	50

7.3 Resources Potential

The NREL has mapped (Figure 7. 1) Pakistan's wind resources with the support of the USAID (Elliott, 2007, p. [slide 15]). Meanwhile, PMD has initiated a program, consisted of two phases. The Ministry of Science and Technology, Pakistan is supporting the program. The program's first phase was focused on the southeast sites and completed by 2005.

In the second phase, PMD is investigating the central and northern areas, and the work is in progress (PMD, [n.d(a)], p. [online]). Furthermore, the World Bank initiated a comprehensive program to re-map the country's wind resources. As per plan, the program is expected to be completed by 2017 (ESMAP, [n.d], p. [online]). In the future, therefore, more information of the resources capacity and wind speed will be available.

To fulfill the data requirements of the research, the information available from AEDB, the USAID, PMD and NASA have all been used. Details of which are discussed in the following sections.

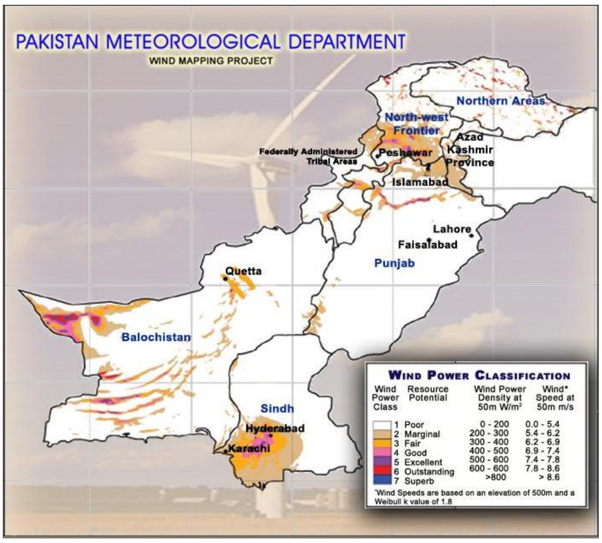

Figure 7. 1: Pakistan's wind resources map
Source: *(Elliott, 2007, p. [slide 05])*

7.3.1 Southeastern Wind Corridor

Pakistan's southeastern wind corridor is located in the Sindh province. The corridor consists of both offshore and onshore resources. However, at present, only the onshore potential is being investigated, and the same has been considered for this research. According to PMD, the onshore covered area of the corridor is 9,700 km^2 and has a total potential of about 43 GW (PMD, 2009, p. ii). In the following paragraphs, the details of the corridor's important onshore sites are explained.

Gharo

The Gharo site is among the most promising sites of the country and has been investigated the most. In 2004, PMD performed a feasibility study of the site for a cost determination. Using a hypothetical turbine of 600 kW, the levelized cost was estimated to be PRS. 2.50 to PRs. 3.0/kWh (i.e., 1.4-1.6 US$ cents/kWh), with a payback period of 7-8 years (Chaudhry et al., 2004, p. 4). PMD has investigated 41 locations at the site (i.e., in the first phase of its program). From the measured data, the annual mean speed at 50 m height is 6.86 m/sec (PMD, 2003, p. 15). For more information, Figure 7. 2 presents the hourly wind speeds of the site (AEDB, [n.d], p. [online]).

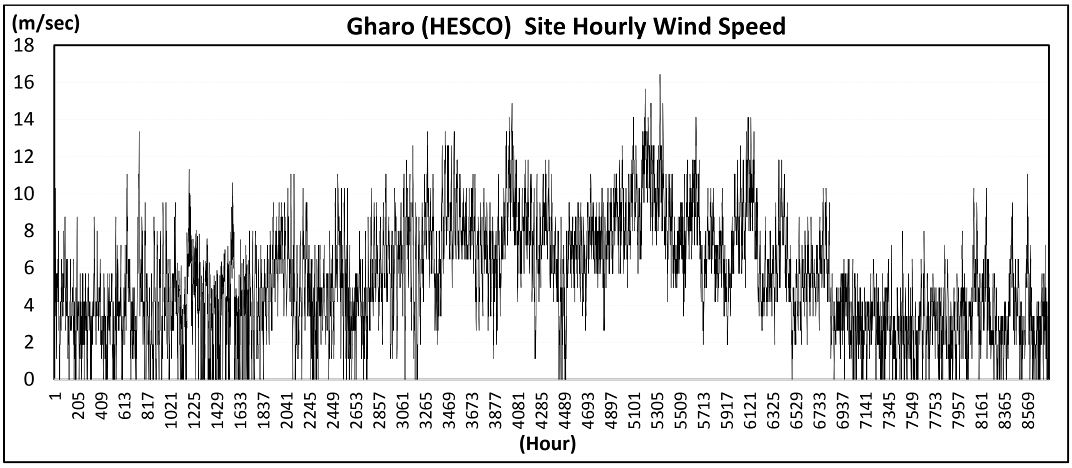

Figure 7. 2: Wind speed recorded at Gharo wind site
Source: (AEDB, [n.d], p. [online])

Jhimpir

The Jhimpir site is an extension of the Gharo site, moving toward the north. From measured data, the capacity factor of the site is assessed to be higher than 40%, using a standard 600 kW wind turbine (PMD, 2009, p. [Table 17]). The two operational wind power projects are at the same site. The site resource availability can be assessed by looking into Figure 7. 3 which shows the hourly wind speeds of the site (AEDB, [n.d], p. [online])[92].

[92] The readings were taken by FFCEL project

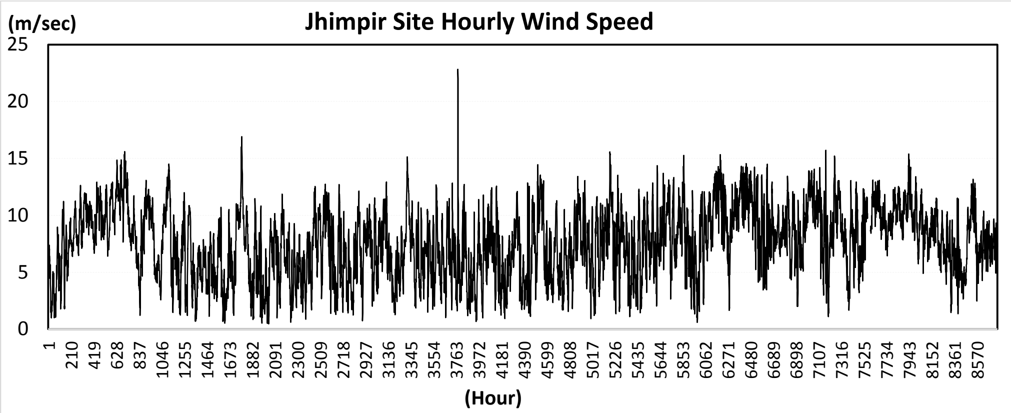

Figure 7. 3: Wind speed recorded at Jhimpir wind site
Source: (AEDB, [n.d], p. [online])

7.3.1.1 Karachi and Adjacent Baluchistan Coastal Areas

Karachi is the most populous city of Pakistan. Outside of the metropolitan area, there is a vast, deserted land. For wind power, the sites of fair and marginal potentials are identified in this area, particularly in the coastal area. The data of three years in the early 2000's (i.e., 2002-2005) indicate that at the site, the annual mean value of the wind speed at 50 m is 4.2 m/sec, with a standard deviation of ±3.3. (PMD, 2005, p. 9). In Figure 7. 4, the wind speed profile of the site is measured at a "minute" resolution and is presented (AEDB, [n.d], p. [online]).

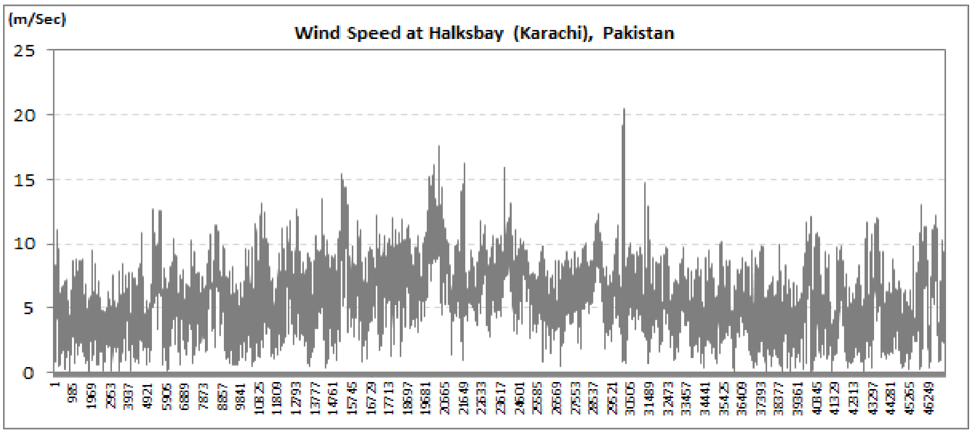

Figure 7. 4: Wind speed recorded at Haksbay, Karachi
Source: (AEDB, [n.d], p. [online])

7.3.2 Baluchistan Wind Sites

The country's southwest wind sites are, mostly, located in the less populous areas. The eastern and central sites are scattered, while the southwestern sites constitute a major corridor. However, the corridor is currently not attractive for an investment due to the lack of infrastructure. In addition, the local electricity demand is so small that the region is electrified through a 100 MW capacity line from Iran and is not connected to the national grid system.

For this research, the NREL database[93] and NASA datasets were accessible sources of information to assess the total potential and wind speed of the sites. The datasets were used in HOMER to generate the speed profiles of the sites. HOMER uses the auto-regression model shown below, in a basic form,[94] and the generated profile of the main site is presented in Figure 7. 5.

$$y_{t+1} = ay_t + \epsilon$$

Where
$a = Regression\ Coefficient$
$\epsilon = Noise\ Function\ N(0, Var)$

7.3.3 Central Pakistan Sites

In central Pakistan, PMD investigated a few sites marked for an assessment of wind energy potential. These sites are scattered and small but are important due to their closeness to the load centers. Additionally, the sites' generation potential is at its highest during the spring and early summer. This period is critical one regarding the renewable resources availability, in Pakistan[95]. In these sites, Kallar Kahar (i.e. Chakwal District) has the maximum potential. In the following, TABLE 7. III present the site's monthly average wind speed at a height of 90 m (F.Ahmad et al., 2014, pp. 714-719). In June 2009, PMD investigated the site with SODAR (Sonic Detection and Ranging) at 85 m height. From which, 6.89 m/sec monthly average wind speed was found, and the hourly wind speed profile as shown in Figure 7. 6 (Chaudhry et al., 2009, p. 6). For an annual hourly speed profile, HOMER was used again.

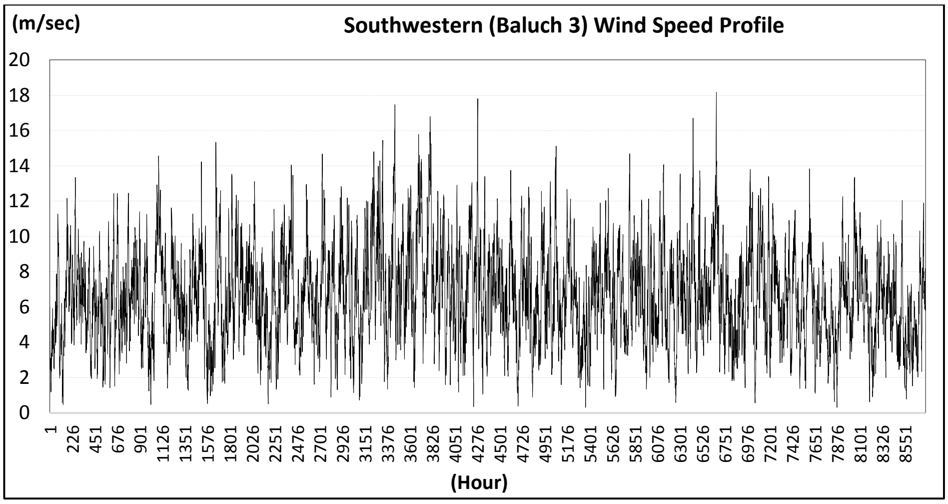

Figure 7. 5: Southwestern Baluchistan wind speed profile, synthetically generated using HOMER with statistical information from (ASDC, 2013(b), p. [online])

[93] The database is developed by NREL, with support from USAID
[94] More details about the approach are available in the "help" of HOMER.
[95] Discussed in the results chapter (i.e., chapter 10) of the thesis

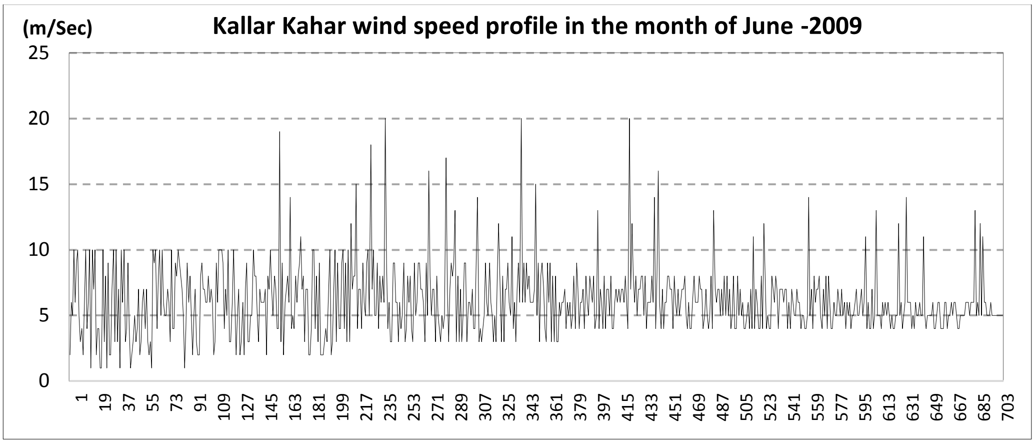

Figure 7. 6: Kallar Kahar hourly wind speed profile of June-2009
Source: (Chaudhry et al., 2009, p. 6).

TABLE 7. III: Monthly mean wind speed at Kallar Kahar, Pakistan (F.Ahmad et al., 2014, pp. 714-719).

Month	Monthly Mean Wind Speed (m/sec)
January	7.00
February	7.04
March	7.87
April	7.82
May	8.71
June	8.65
July	6.92
August	5.32
September	6.25
October	7.35
November	7.14
December	6.63

7.3.4 Northern Pakistan Wind Sites

As mentioned earlier, the second phase of PMD's program is currently focused on the northern parts of the country. There, the sites are scattered, but located closer to the areas of the hydropower potential. The resources, therefore, can be used conveniently in combination with the PHES system.

In the following TABLE 7. IV the annual average wind speed and the capacity factor of a few important sites are presented (PMD, n.d(b), p. [online]). For wind speed, the PMD investigated the Ayun station from March 2007 to February 2008 (Chaudhry et al., 2009a, pp. 7,23). The measured statistical information of the investigation was manipulated, to generate the hourly wind speed profile (Figure 7. 7) using HOMER. In this analysis of the research, the same pattern was used for all other sites of the region.

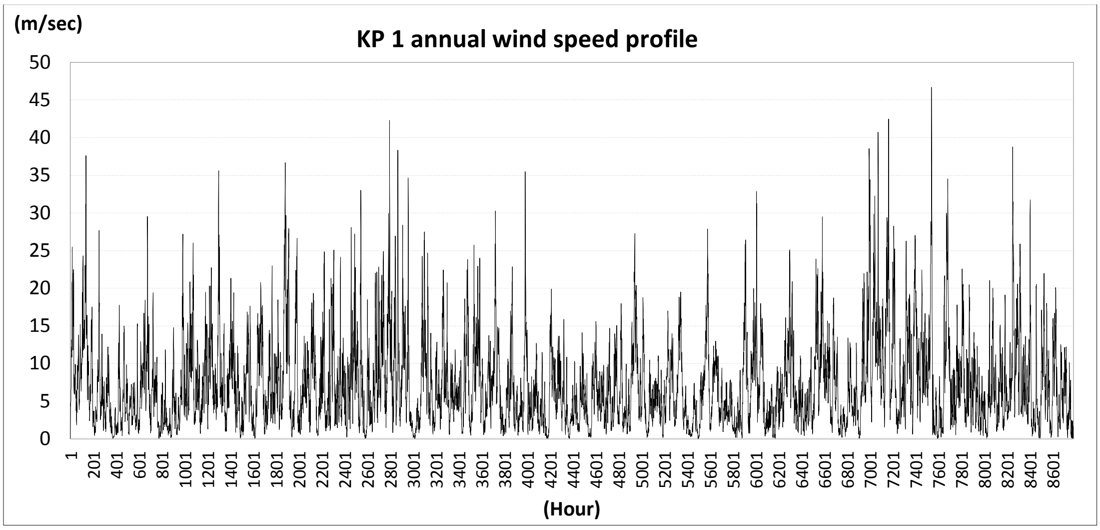

Figure 7. 7: Ayun site wind speed profile generated by using HOMER with information (i.e., Weibull parameter) from: (Chaudhry et al., A Study of Wind Power Potential at Ayun-Chitral, 2009a, p. 23).

TABLE 7. IV: Northern Pakistan wind sites and their mean wind speed (PMD, n.d(b), p. [Online]).

Station	Mean Wind Speed (m/sec)	Capacity Factor (%)
Sheedgali	5.39	18
Fatehpur	4.91	14
Dargai	4.51	13
Shahida Sir	4.6	13
Besham Qila	4.69	13
Ayun	3.93	9
Chitral	3.02	8
Khyber, FATA	3.34	6
Moorti Pahari Rwp.	4.26	11

7.4 Total Potential

PMD uses the GIS mapping database, developed by the NREL, as a reference source for information regarding the wind resources in Pakistan. In the database, the details are available at the provincial level[96], and the total potential is categorized according to the resources quality (NREL, 2006, p. [Database]). The NREL has used several data sources, including; surface station data, upper air station data, satellite derived ocean wind data, marine climate atlas of the world, etc., to prepare the database. Furthermore, the information has been treated with the numerical wind flow model (i.e. CALMET) and different empirical and analytical techniques for improvements (Elliott, 2007, p. 07).

[96]It is a Geospatial Toolkit, developed by NREL and USAID

For this research, the assessed potential of the database is given in Figure 7. 9. When compared to the total, the exploitable capacity can be different due to constraints or limitations. Fortunately, in Pakistan, the major wind sites are located in the relatively less populous areas, particularly in the southwest regions (Figure 7. 8). Still, in the analysis, two potential values were considered to incorporate the uncertainty of the resources availability. The values were 40% (i.e., 1.2% of the land area) and 80% (2.4% of the land area) of the total potential, as presented in TABLE 7. V (NREL, 2006, p. [DB]). These cases are referred to as low wind (LW_Supply_Case) and high wind (HW_Supply_Case) in the upcoming chapters of this thesis.

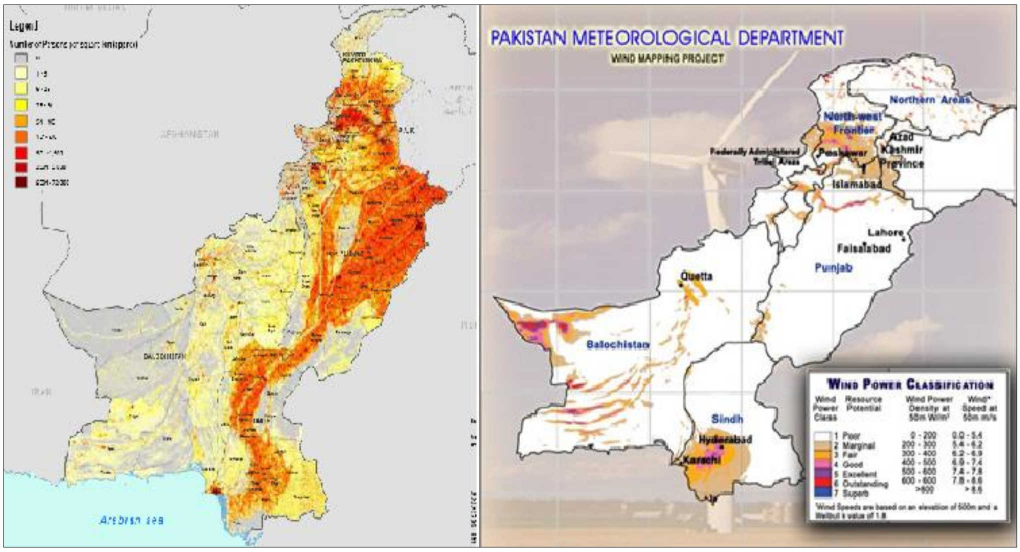

Figure 7. 8: Pakistan's population density and wind resources maps
Source: (IFC, [n.d], p. 10) , (NREL, 2006, p. [Database])

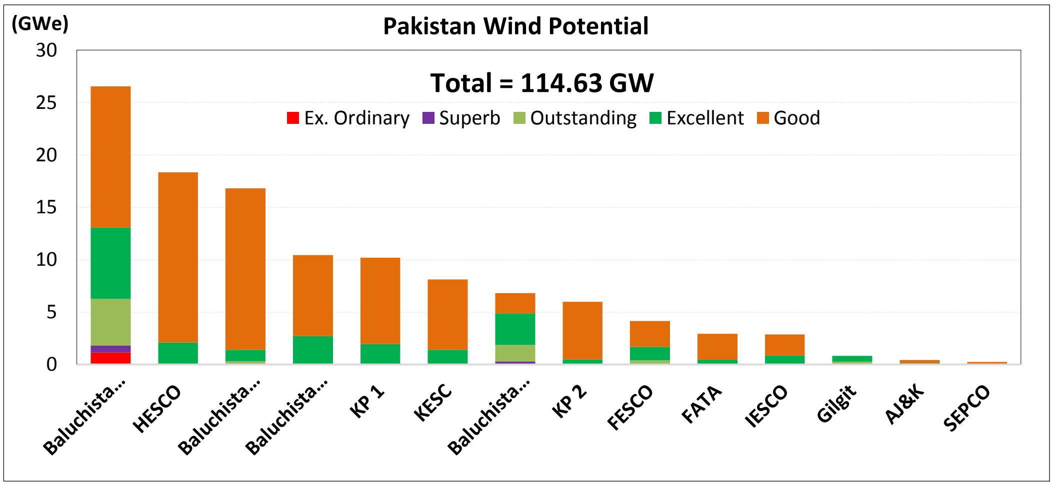

Figure 7. 9: Wind resource potential of different Class in the Regions. In the figure, the classification start from Good (400-500 W/m²) and each of the next class covered a range of 100 W/m²
Source: (NREL, 2006, p. [Database])

TABLE 7. V: Regional wind potential assessment in Pakistan (NREL, 2006, p. [Database]).

Regions	NREL Potential (GW)	High Wind (HW) _Supply_Case (GW)	Low Wind (LW) _Supply_Case (GW)
AJ&K	0.4	0.3	0.2
Baluchistan1	16.8	13.5	6.7
Baluchistan2	10.4	8.3	4.2
Baluchistan3	26.6	21.2	10.6
Baluchistan4	6.8	5.4	2.7
KESC	8.1	6.5	3.3
HESCO	18.3	14.7	7.3
SEPCO	0.2	0.2	0.1
FATA	2.9	2.3	1.2
KP1	10.2	8.1	4.1
KP2	6.0	4.8	2.4
Gilgit	0.8	0.6	0.3
FESCO	4.1	3.3	1.7
IESCO	2.9	2.3	1.2
Total	**114.6**	**91.7**	**45.9**

Chapter Summary

The potential of the wind resources in Pakistan is estimated to be around 115 GW, mostly existing in the southern parts. Besides the southwestern sites, PMD investigated the rest of Pakistan for an assessment of the potential. Furthermore, another project supported by the World Bank is also in progress to re-map the resources. Currently, there are two operational wind farms of a total 104 MW capacity in Jhimpir (i.e., southern site). The sites capacity factor is above 30%, based on a standard 1.8 MW wind turbine.

The potentials of the central and the northern areas are in the range of good to marginal. However, the sites are important due their closeness to the load centers or to the potential PHES locations. The resources, therefore, can efficiently contribute to the development of a 100% renewable electric supply system. In the analysis, two different values of the resources have been considered due to a lack of information regarding their exploitability. In the "LW_Supply_Case", the value was 40% of the total potential, while in the "HW_Supply_Case", it was 80%.

Chapter 08: Pakistan's Biomass Resources

In Pakistan, biomass is a big source of energy. Its major consumer is the residential sector of the rural and semi-urban areas. According to IEA (2012, p. 407), 64% population of the country had been using traditional biomass for cooking by the year 2010[97]. In this chapter, the potential of these resources are discussed. Furthermore, this chapter describes the ongoing efforts regarding such resource development in Pakistan.

8.1 Biomass Potential and Use in Pakistan

8.1.1 Wood

Wood is an important form of energy in the rural areas of Pakistan, and is mostly collected from forests. However, its consumption is gradually increasing. Since 2000, the country's forested areas have decreased by 0.1%, due to a growth in demand (World Bank, [n.d], p. [online]). The decrease indicates the scale of deforestation, as the GOP manages the efforts of plantation, conservation, and management[98] (Baig et al., 2008, pp. 167-183). According to the UNDP (2010, p. 229), the wood consumption in the country can be distributed as 82% residential, 15% industrial and 3% commercial. The consumption of wood as fuel was assessed to be 34.95 million cubic meter (MCM) in the country as of 2011 (Zaman & Ahmad, 2011, p. [Table 1]).

8.1.2 Agricultural Residue

Pakistan is an agricultural country (Ministry of Finance, 2013, p. 18). The sector generates a significant quantity of the crop's residues, which are used for different purposes, including the following ones (Kojacovic & Maltsoglou, 2014, p. 9);

- As an energy source, particularly in the rural areas.
- Some types of residues are used as animal fodder.
- In the construction of homes.
- As an option to enrich soil nutrients.

Currently, the industrial sector of Pakistan uses bagasse for captive power generation and the installed capacity (TABLE 8. I) is around 191 MW (NEPRA, 2009, p. 24). In addition, the GOP has planned to connect 83 sugar mills to the national grid system. From which, 3000 MWe bagasse based power will be available for the system (PPIB, 2008a, p. 9).

[97] Biomass is used in all forms for cooking, including wood, dung cake, agriculture residue, etc.
[98] The country current forest area is around 115,360 km^2

TABLE 8. I: Bagasse based installed power generation capacity in Pakistan (NEPRA, 2009, p. 24)

Sr. No.	Project Name	Capacity (MW)
1	Al Moiz Industries Limited	27
2	Indus Sugar Mills	11
3	Shakarganj Energy (Private) Limited	20
4	JDW Sugar Mills (Private) Limited	22
5	Ghotki Sugar Mills (Private) Limited	12
6	Ramzan Sugar Mills Limited	12
7	Ashraf Sugar Mills Limited	8
8	The Thal Industries Corporation Limited	9.2
9	Al-Noor Sugar Mills Limited	22.65
10	Brother Sugar Mills Limited	13
11	Hamza Sugar Mill	19.6
12	Sugar Mill Dhabeji	15
	Total	**191.45**

There are several other crop residues, particularly cotton sticks and rice straw, which can potentially be used for power generation. Recently, the World Bank initiated a project for an assessment of the residues availability for power generation (Kojacovic & Maltsoglou, 2014, p. 29)[99]. According to the scope report of the project, information is ambiguous regarding the availability of the residue, a survey and thorough analysis is needed.

Still, to get an idea, the total potentials of the three main residues, based on their crops production, are presented in TABLE 8. II. The calculations are based on the following assumptions:

- All three residues are available for power generation.
- The power plant efficiency is 35%.
- The conversion and transportation wastages factors were assumed to be 0.1 for bagasse and 0.2 for cotton and rice residues.

8.1.1 Livestock Manure

Pakistan is the world's fifth largest producer of milk[100] (Beldman & Alfons, 2013, p. [online]). The country's historical data (Figure 8. 1) show that both the production of milk and livestock population is steadily growing (Ministry of Finance, 2013; 2014, p. [Table 2.14]).Pakistan's livestock generates a significant quantity of manure, that can potentially be converted into a burnable gas form and then used for power generation. Using a 60% collection factor and 40% power plant efficiency, the total potential based on the current livestock population is around 22 TWh (TABLE 8. III).

[99] The project is part of the country renewable resources re-mapping project, of the World Bank.
[100] The top four are Russia, USA, China and India

TABLE 8. II: Pakistan's agriculture sector estimated biomass residue and potential of energy generation

Crop	**2012-13 Annual Production (million kg),** (Ministry of Finance, 2014, p. [Table 2.4])	**Residue Type** (Bhutto et al., 2011, pp. 3207-3219)	**Residue to Crop Ratio (Residue in kg /kg Crop)** (Bhutto et al., 2011, pp. 3207-3219)	**Total Residue (million kg)**	**Res. Calorific Value (MJ per kg)*** (IPCC, 1996, p. [1.45])	**Net Elec. Potential (TWh)**
Sugarcane	63,750	Bagasse	0.33	21037.5	16.2	**29.82**
	63,750	Top & Leaves	0.05	3187.5	16.2	**4.52**
Cotton	2,214	Boll Shell	1.1	2435.4	11.9	**1.97**
	2,214	Husk	1.1	2435.4	9.8	**1.62**
	2,214	Stalk	3.8	8413.2	11.9	**6.81**
Rice	5,536	Husks	0.2	1107.2	14.4	**1.09**
	5,536	Stalks	1.5	8304	11.7	**6.61**
	5,536	Straw	1.1	8304	11.7	**6.61**
Total	**150750**			**55,224.2**		**59.06**

* Net calorific values are based on air dry basis of the residue

TABLE 8. III: Electricity generation potential from livestock manure in Pakistan

/	**Buffaloes and Cattle**	**Goat and Sheep**	**Poultry**	**Total**	**Reference**
Population (million)	72	93.7	785	----- -----	(Ministry of Finance, 2014, p. [Table 2.14])
Manure/Yr./Unit (tonnes)	3.6	0.7	0.022		(Overend & Milbrandt, 2011, pp. 15-16), (SGC, 2012, p. 07)
Manure Available (million tonnes)	155.52	39.35	10.36	**205.236**	
Conversion Coefficient (m3/tonne)	33	58	78	------	
Heating Value (kWh/nm^3)*	6.63	6.63	6.63	------	
Annual Electricity (TWh)	13.61	6.05	2.14	**21.80**	

*In nm3-n stands for normal i.e., 1.03 bar pressure and 0^{o}C.

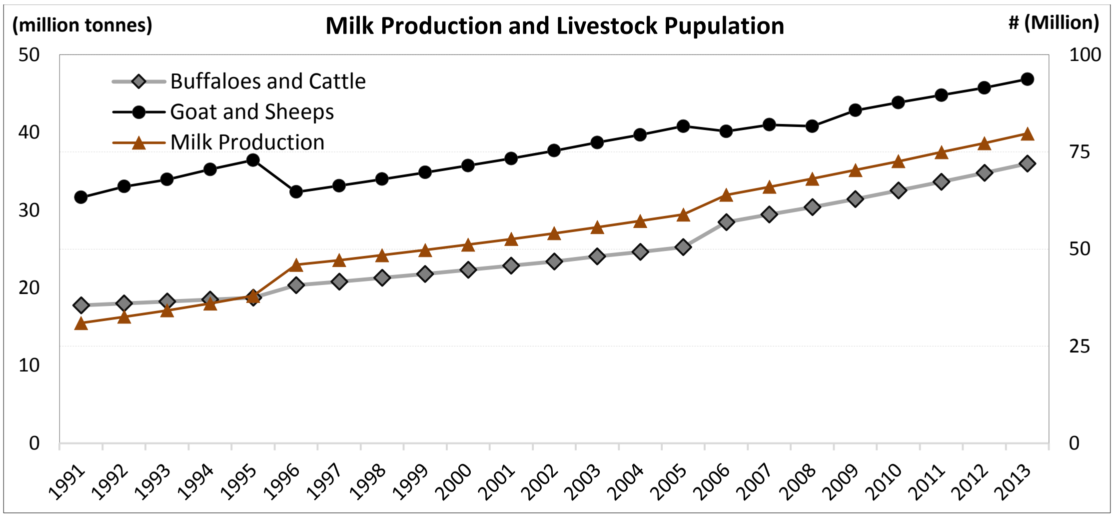

Figure 8. 1: Milk production and livestock population in Pakistan

Source: (Ministry of Finance, 2013; 2014, p. [Table 2.14])

8.1.2 Municipal Solid Waste

Generally, residential, commercial, and the industrial sectors generate municipality wastes in different forms, and, therefore, both population growth and development contribute to the mass of waste. Pakistan current population is about 188 million and the rural community makes up around 61.4% of the total (Ministry of Finance, 2014, p. [Table 12.2]). Still, some of the urban centers are highly populated (TABLE 8. IV). These urban centers play a large role in the total waste production[101], but the waste physical compositions are different from one city to another. To highlight the differences, the waste compositions by weight of the five cities are shown in Figure 8. 2 (PEPA, 2014, p. [Table 4]).

TABLE 8. IV: Pakistan's major cities and their population

Rank	City	Population (# million)	
		1998* (Federal Bureau of Statistics, 2006, p. 28)	**2012**** (Ministry of Finance, 2014, p. [Table 12.2])
1	Karachi	9.339	12.75
2	Lahore	5.443	7.43
3	Faisalabad	2.009	2.74
4	Rawalpindi	1.41	1.93
5	Multan	1.197	1.63
6	Hyderabad	1.167	1.59
7	Gujranwala	1.133	1.55
8	Peshawar	0.983	1.34
9	Quetta	0.565	0.77
10	Islamabad	0.529	0.72
11	Sargodha	0.458	0.63
12	Sialkot	0.422	0.58

* Based on census   ** Based on Survey

[101] For management of the wastes, the GOP established Pakistan Environmental Protection Agency (PEPA) with support from Japan International Cooperation Agency (JICA) and UNDP.

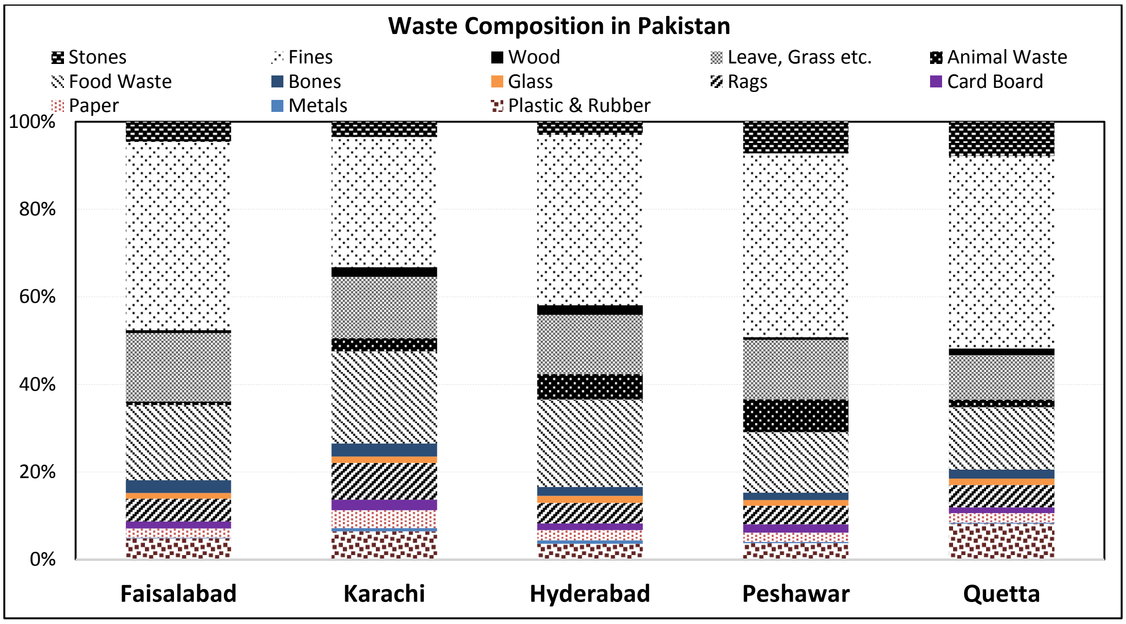

Figure 8. 2: Waste composition by weight in Pakistan
Source: (PEPA, 2014, p. [Table 4])

Generally, the generation of waste in a municipality depends on the social development and behavior of the inhabitants. Still, it is estimated that in Pakistan, 0.4-0.6 kg waste per capita per day is generated in the urban areas, while 0.2-0.3 kg per capita per day in the rural areas (PEPA, 2014, p. [Table 4]). Based on these figures, the estimated values of the major cities municipality waste are given in TABLE 8. V.

To manage the waste, most of the municipalities cover it in earth. According to AEDB, the landfilling generated 3.6 million tonnes CO_{2eq} Methane (CH_4) gas in the country during 2012. The gas deteriorates the general environment and likely to be noticed. Recently, the board initiated some efforts to develop the country's first waste based power generation project. In this regard, the board has finalized a NAMA (national appropriate mitigation actions) of the waste sector (AEDB, 2013, p. n.p).

TABLE 8. V: Pakistan major cities municipality waste generation (PEPA, 2014, p. [n.p]).

Cities	**Waste Generation**	
	kg/Person/Day (PEPA, 2014, p. [Table 2])	Total (million kg) by 2012
Karachi	0.6	2853.0
Faisalabad	0.4	391.5
Hyderabad	0.6	327.4
Gujranwala	0.5	264.8
Peshawar	0.5	239.6
Quetta	0.4	106.4
Country (Total)	**0.3**	**19,127.1**

8.2 History of Biogas Development in Pakistan

8.2.1 GOP Efforts

The history of biogas generation in Pakistan is more than 35 years old. In the country, PCAT (Pakistan Council of Appropriate Technology) was the first organization to experimentally use biogas technology in Pakistan. They installed 350 biomass gasifiers of different designs and found the movable gasholder (MG) an appropriate one.

In the early 1980s, a newly established directorate of the DGNRER (Directorate Generals of New and Renewable Energy Resources) took the responsibility of the biogas technology development (PCRET, 2014, p. [n.p]). The DGNRER promoted the technology in the rural areas through a scheme of three phases, with a focus on big size units (PCRET, 2014, p. [n.p]). In the first phase, 100 demonstration units were installed free of charge to beneficiaries. In the next phase, the cost was subsidized, and then finally, the subsidy was withdrawn in the third phase. Under this scheme, 4000 units were installed by 1986 (Ghimire, 2007, p. 1).

In 1993, the GOP dismantled the DGNRER and renamed PCAT as PCRET (Pakistan Centre for Renewable Energy Technologies). The main objective of PCRET was to commercialize and disseminate the technology throughout the country. Since then, PCRET has been promoting the technology (PCRET, 2014, p. [n.p]). In the period of 2002-2006, PCRET installed 1,600 biomass gasifiers in the country, following a target of 4100 by 2008 (Ghimire, 2007, p. 11).

8.2.2 Non-Governmental Organizations (NGOs) Efforts

Recently, a few NGOs initiated their programs for the eradication of energy poverty and for the provision of clean energy technologies in the rural areas of Pakistan. Their programs are either independent or a joint venture, working with the government. In these NGOs, one is the IRSD (Initiative for Rural and Sustainable Development), which is supported by the UNDP. They have installed around 150 units in different areas of the country. Furthermore, FIDA (Foundation for Integrated Development Action) and the RSPN (Rural Support Program-Network) are also working with the same objectives in the low income rural areas of Pakistan (Ghimire, 2007, p. 11).

8.3 Prospects of Biomass in Pakistan

In the future, the potential of biomass can grow due to the following main reasons;

I. The country's current area of agrarian activities is around 220,700 km^2, while the total potential land is about 303,400 km^2 (PBS, [n.d (a)], p. [Table 3]). In the future, the activities can rise to meet a growing demand of the agricultural commodities (i.e., food).

In this case, the agricultural residues will increase by a factor of 1.36, if the total arable land is utilized.

II. In Pakistan, the current yield of the agriculture sector is around 0.8 of the nominal value due to many factors, including the use of conventional farming methods (Arifullah et al., 2009, p. 613). In the future, the value can reach to a nominal limit by using modern technologies and good seeds. In this case, the agricultural residue will also grow.

III. Pakistan's population is expected to be around 244.92 million by 2030 and 309.64 million by 2050 (UNO, 2015, p. 21). This will result in the growth of municipal waste and livestock population. A proper management of the two biomass forms can further increase the resources potential in the country.

8.4 Biomass as a Seasonal Storage Option

In this research, biomass resources are considered as a potential option for balancing the demand across a year, due to its quality of control generation. However, the issues of ramping rate and cool start imposing limitations on its use as a load-following supply source. In the analysis, therefore, the option was dealt exogenously in the simulation of the demand-supply balance. More details of the approach used for the purpose are given in the "System Simulation and Demand-Supply Balance" chapter of the thesis.

8.5 Chapter Summary

Pakistan is basically an agricultural country, and therefore has enough biomass resources. In the future, the resources can grow due to the availability of the potential agrarian land and population growth. The resources mainly consist of wood, crop residues, and livestock manure. In the rural areas, the resources fulfill a major share of the household sector energy demand. In addition, there is a limited use of the bagasse for power generation in the industrial sector.

In Pakistan, biomass to gas conversion technology has been experimented for several decades and is already being employed, particularly in the rural areas. Furthermore, there is also a potential of power generation using the municipality wastages and the AEDB is working toward its development.

Chapter 09: Demand Forecasting

The electricity demand of Pakistan by 2050 was required for the analysis of the demand-supply balance, as mentioned earlier. This chapter presents the efforts to forecast what demand in the future can be. For the forecasting, the year 2012 was taken as the base year. Since the time horizon of the forecasting is long (i.e., 38 years), having accurate up-to-date forecasted values in time for this analysis is unlikely. To overcome this uncertainty, the demand was forecasted in two different scenarios of the economic growth i.e., an optimal growth scenario (OG_Scenario) and a high growth scenario (HG_Scenario). More details of the scenarios and their corresponding demand values are discussed in this chapter.

9.1 Basic Information

9.1.1 Economy

Pakistan is a developing country and its population was around180.7 million by 2012. By the same year, the county's total real GDP was 9,524 billion PRS in the basic prices of 2005-06 (Ministry of Finance, 2014, p. [Table 1.1]). In the past, the economy was dominated by the agriculture sector along with the commodity producing sectors. However, the sector share gradually decreased due to relatively high growth in the services sector as shown in Figure 9. 1.The figure also shows that the industrial sector almost maintained its share through a firm growth across the period (Ministry of Finance, 2007, p. 09; 2014, p. 06).

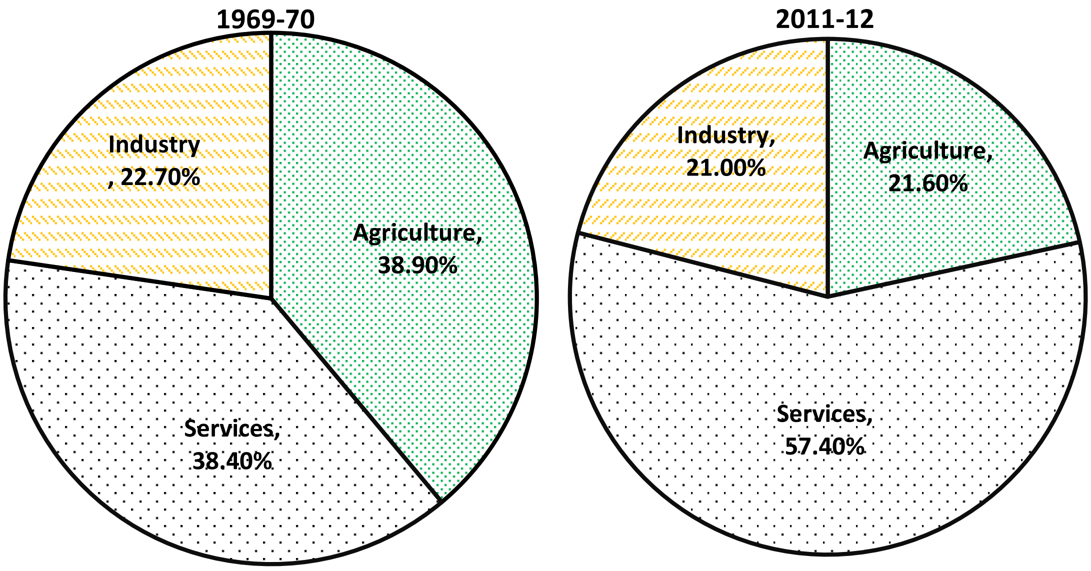

Figure 9. 1: Pakistan major economic sectors and their shares in the total GDP
Source: (Ministry of Finance, 2007, p. 09; 2014, p. 06).

9.1.2 Electricity Generation and Demand

9.1.2.1 Generation Mix

In the supply mix of Pakistan's power system, substantial shares consist of oil, gas, and hydropower, as shown in Figure 9. 2 (HDIP, 2013, p. 03). In the figure, a small contribution of the nuclear generation and negligible shares of imports and coal can also be seen. The imports represent the electricity, which was supplied by the Iranian power system to the border regions (i.e., southwestern parts) of Pakistan[102].

9.1.2.2 Load Shedding

Pakistan had a total installed capacity of 22,797 MW[103] by 2012 (HDIP, 2013, p. 03). Despite a sufficient installed capacity, the country was facing severe power supply crises. During the summer, the supply system faced a shortage of up to 7,000 MW during peak demand hours[104]. The system served a peak of just 15,062 MW, while the peak demands was up to 18,940 MW[105] (NTDC, 2012, p. 32). During the year, the system total load-shedding was assessed to be around 25-30 TWh (NTDC, 2011c, p. 1(1)).

9.1.2.3 Electricity Total Demand

Pakistan's final electricity consumption was around 76.7 TWh by 2012 (HDIP, 2013, p. 84). Considering the load-shedding share of the residential sector[106], the demand is assessed to be 81 TWh by the base year. Since the load-shedding of other sectors are reflected through a decrease in their GDP, their values are not included. This made the sectoral consumption intensities (i.e., energy consumption per unit GDP contribution) accurate one.

9.1.3 Base Year Electricity Consumption Intensities

Pakistan's major electricity consumption sectors are agriculture, residential, services and industry. In addition, a few minor sectors, including, construction, mining, and fishery also exist, but their volumes are small. For convenience, they are considered as sub-sectors of the before mentioned four major ones. The construction and the mining sectors were counted in the industrial sector, while the fishery sector in the agriculture sector. Pakistan's transport sector (i.e., railway) consumes a negligible amount of the electricity. In this research, the sector (i.e., railway) consumption intensity is calculated with respect to the total economic growth and assumed to be driven by it. In TABLE 9. I, the sectoral intensities, found in the base year, are presented.

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[102] Pakistan imports electricity from Iran, to fulfill the basic needs of remote rural areas, near Pak-Iran border.
[103] In this total, thermal installed capacity was 15,454 MW and hydro was 6627 MW.
[104] It is generally a high hydro generation period.
[105] Computed demand is approximated from actual plus demand not served
[106] Residential sector share in the load-shedding is assumed to be according to its share in the total demand.

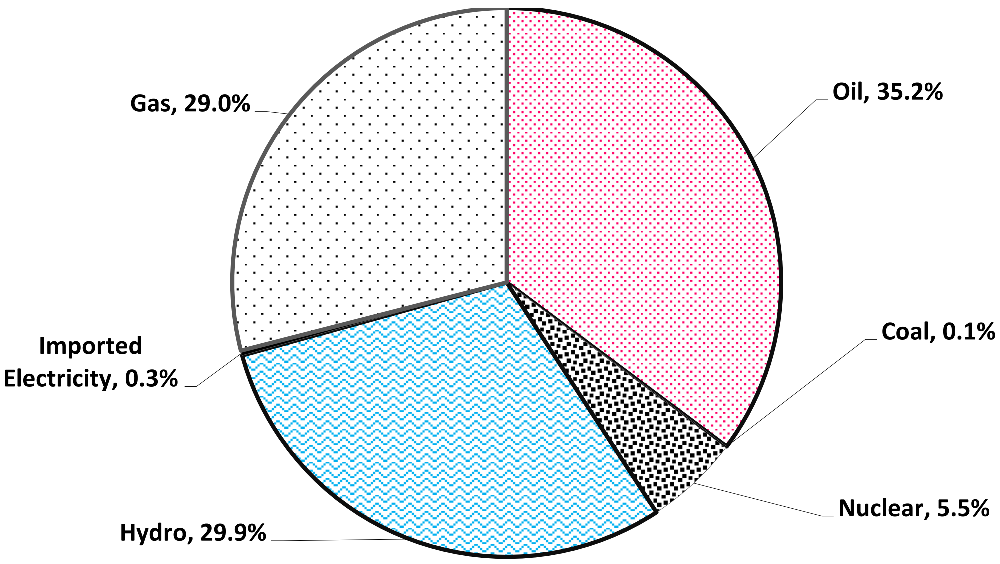

Figure 9. 2: Pakistan electricity supply system mix by 2012
Source: (HDIP, 2013, p. 03)

TABLE 9. I: Electricity consumption intensities in the base year (i.e., 2012)

Sectors	Services	Industry	Agriculture	Residential*	Transport**	References
Consumption (GWh)	10,822	21,801	8,548	35,589	1	(HDIP, 2013, p. 84), (Ministry of Finance, 2014, p. [Table 12.1])
GDP (million PRs.)	5,490,000	1,989,000	2,045,000	-	-	
Intensity (kWh/PRs.)	0.00197	0.0109	0.00417	189 per cap.	1.04998E-07	

*The electricity consumption intensity of the residential sector is given in kWh per capita
** The GDP contribution of the transport sector is part of the commercial sector, as it is reported in the way by the government

9.2 Electricity Demand Forecast

NTDC, Pakistan regularly forecasts and publishes the electricity demand forecast of the country. Generally, they assume a substantial growth in the economy and frequently revise the figures, as often as every three to five years (NTDC, 2008; 2011b). In these circumstances, use of the values for a time horizon of 35-40 years was not reasonable. Consequently, the task was carried out in the research using the following information.

9.2.1 Demand Drivers

9.2.1.1 Residential Sector

Generally, for a residential sector, population growth and lifestyle improvement are the demand drivers. Pakistan's historical data (Figure 9. 3) shows that the annual growth rate of population (PAGR) is decreasing (Ministry of Finance, 2014, p. [Table 12.1])[107]. According to UNO (2015, p. 21), Pakistan's total population is projected to be 244.92 million by 2030 and 309.64 million by 2050. For this research, the values have been used to forecast the sector

[107] In this figure, its look like that 2005 PAGR is under while 2007 is over reported. This may be because the figures are based on survey, and therefore, the higher value of 2007compensate for 2005 low value.

electricity demand by 2050. For an assessment of lifestyle improvement, the per capita consumption relative to the GDP growth was assessed, which is discussed in the upcoming sections (i.e., future intensities) of the chapter.

9.2.1.2 Economic Sectors

In general, consumptions of economic sectors are driven by their production. In Pak-IEM, the Planning Commission of Pakistan has used the forecasted GDP growth rates for the period 2010-2030 (Figure 9. 4) and has assumed a constant growth rate for the later period (i.e., 2030-2045) (Planning Commission, 2010b, p. 100). The forecasted values suggest an overall average annual growth rate (OAAGR) of 6.0% for the period (i.e., 2010-2045). However, the figures are reported as being "quiet aggressive" in the project report, particularly taking a growth rate of 9-10% in the industrial sector for a period of 30 years (i.e., 2020-2050). Consequently, two further GDP scenarios have been developed with OAAGR 5.0% and 4.2% in the model (Planning Commission, 2010a, pp. 10,22).

In addition, a comparison of the recent past growth rates with the forecasted values, revealed a noticeable difference between the two. The forecasted values, particularly of the industrial sector, are significantly high side (Figure 9. 5). For these reasons, the country recently developed a new framework of the economic growth. Which will be used to set the future development targets based on available resources and opportunities (GOP, 2011). In this situation, it was less practical to use the commission forecasted values of the GDP growths.

As an alternative, the demand was forecasted in two demand scenarios with OAAGR 4.2% and 5%, due to the following reasons.

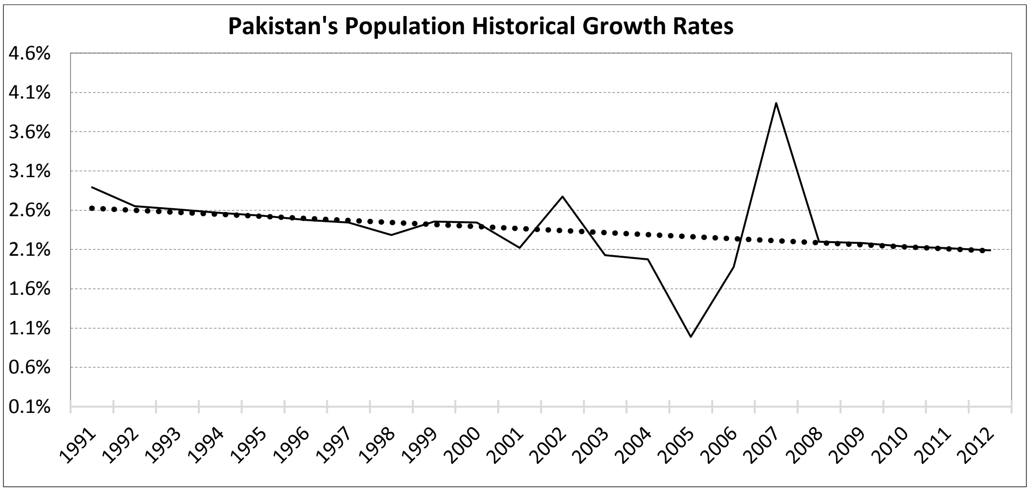

Figure 9. 3: Pakistan's population historical annual growth rate
Source: (Ministry of Finance, 2014, p. [Table 12.1])

I. Historical data of the last twenty years showed an OAAGR of 4.25% in the country's economy (PBS, [n.d], p. [online]).

II. A recent study of the PricewaterhouseCooper[108] (PwC) suggested an OAAGR of 4.3% from 2014 to 2050 for the country (PWC, 2015, p. 18).

III. The two derived scenarios of Pak-IEM used 4.2% and 5% OAAGR as mentioned before.

The assumption of 4.2% and 5.0% OAAGR, therefore, covered the most probable band of the future economic growth. In the following, the two scenarios are briefly introduced, while their summary is presented in TABLE 9. II.

Optimum Growth Scenario (OG_Scenario): In the scenario, a rate of 4.2% OAAGR was assumed, with a rate of 4.0% OAAGR of the industrial sector and 4.5% of the commercial sector. Relatively, the scenario is highly probable in the view of the historical performance of the country's economy.

High Growth Scenario (HG_Scenario): In this scenario, the values of the OAAGR in all the three economic sectors were relatively high (TABLE 9. II). Based on these assumptions, the overall OAAGR of the system across the horizon was found to be 5.0% in the scenario. The scenario looks to be highly optimistic in the view of the economy historical performance, however, the objective of the assumption was to assess the supply system behavior in a more challenging situation by 2050.

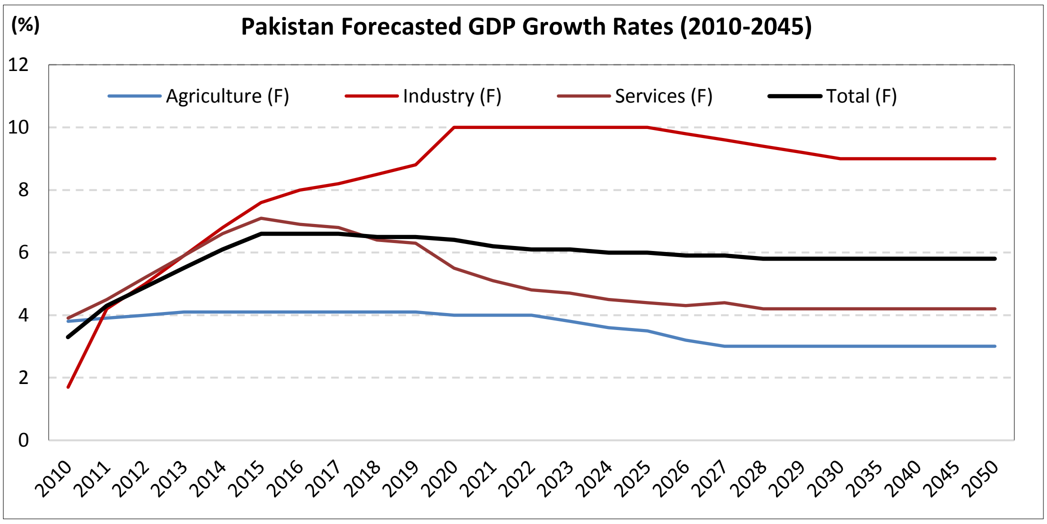

Figure 9. 4: Forecasted and assessed GDP growth of Pakistan
Source: (Planning Commission, 2010b, p. 100).

[108] PwC LLP is a multinational consultant company, and the mentioned report is prepared in the UK.

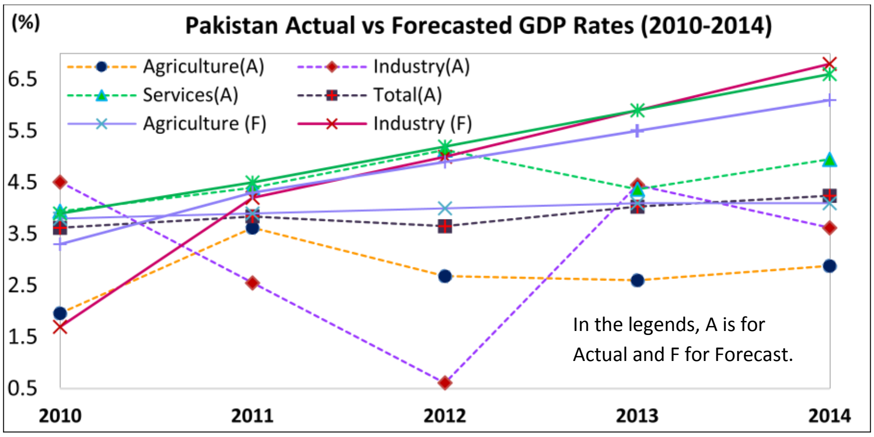

Figure 9. 5: A comparison of forecasted and actual GDP growth rates
Source: (Planning Commission, 2010b, pp. 87-89), (Ministry of Finance, 2014, p. [Table 1.1])

9.2.2 Future Intensities

9.2.2.1 Residential Sector

For lifestyle improvement, the per capita consumption of electricity is a good indicator. In Pakistan, the consumption of the sector was about 199 kWh by 2012, as mentioned earlier. Including the load-shedding factor, the value was estimated to be around 220 kWh. Generally, the electricity consumption in a residential sector is driven by per capita income, and the income is correlated with GDP per capita. This general argument was verified by looking into the historical data of Pakistan, as shown in Figure 9. 7 (NTDC, 2012, p. 64). The figure shows that the consumption of the residential sector rationally increased with the economic growth (i.e., increase in the consumptions of the economic sectors).

TABLE 9. II: Overall average annual GDP growth rates in the two demand scenarios

Summary	OG_Scenario	HG_Scenario
Agriculture	3.0%	3.3%
Industry	4.0%	4.7%
Services	4.5%	5.5%
Total	**4.2%**	**5.0%**

While developing Pak-IEM, a 100% electrification and 1,612 kWh per capita consumption by 2030 was considered (Planning Commission, 2010a, p. 46). However, the per capita value corresponds to the “Reference Scenario” of the GDP growth, in which the values of the OAAGR are quite aggressive. Consequently, the forecasted value (i.e., 520 kWh per capita) of 2012 is almost double that of the actual one.

To approximate the value by 2050, a relationship between per capita GDP and per capita electricity consumption was developed using historical data (Figure 9. 6). In this relationship, the load shedding component was also added to the electricity consumption. Additionally, it was assumed that the sector will be 99% electrified by 2050, which is currently only about

91% (World Bank, 2014, p. [Online]). From this relationship, the per capita electricity consumptions was assessed to be about 769 kWh and 1003 kWh in the "OG_Senario" and "HG_Scenario" respectively by 2050.

9.2.2.2 Economic Sectors

The electricity consumption intensities of the economic sectors are relatively less sensitive to the economic growth rate, but change more obviously due to technological development and fuel switching. In Pak-IEM, these intensities are forecasted for the 2030, using available information and the experts' judgements/opinions (Planning Commission, 2010c, pp. 17,19,23..). In this research, the same values of the intensities were considered during the period. Beyond 2030, the industrial sector and commercial sector intensity was maintained to be the same beyond 2030, despite the fact that the intensity previously decreased. The values of the agriculture sector were extrapolated, as in Pak-IEM, the intensities are assessed to be increasing (TABLE 9. III) [109]. Consequently, the assumption resulted in a relatively higher demand value.

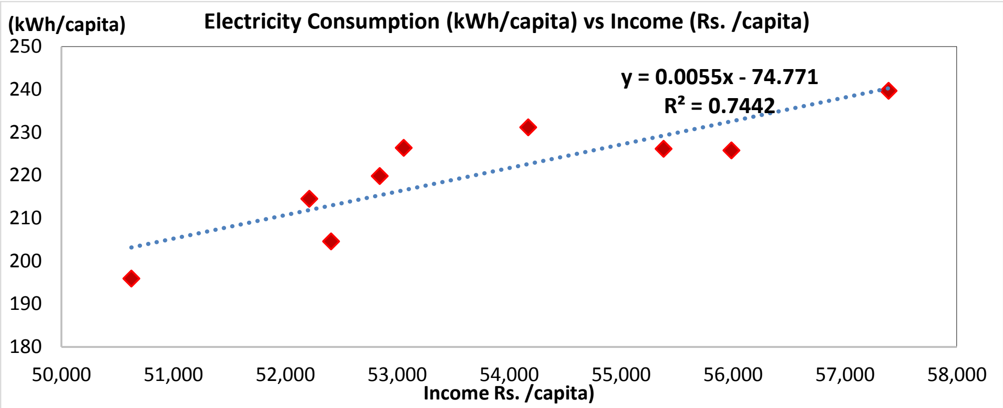

Figure 9. 6: Historical per capita GDP and electricity consumption in Pakistan, Source: (Ministry of Finance, 2014, pp. [Table 12.1],[Table 1.1]), (NTDC, 2012, p. 66)

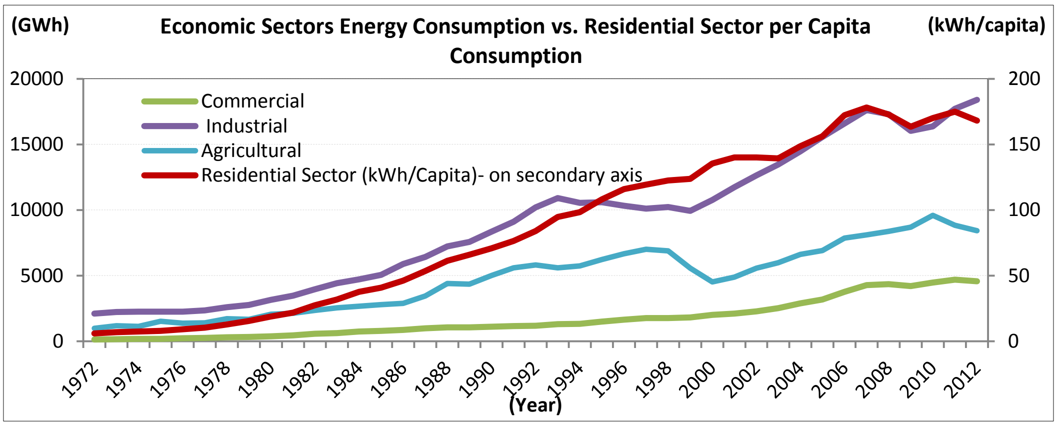

Figure 9. 7: Historical trend of electricity consumption in different sectors of Pakistan Source: (NTDC, 2012, p. 64)

[109] The intensity of grid electricity use in the country in different sectors may decrease due to an increase in the PV technology use, particularly in the residential and agriculture sectors (Author Observations).

TABLE 9. III: Future electricity consumption intensities in different sectors of Pakistan by 2050 (kWh/Pak. Rs)

Year	Commercial	Industry	Agriculture	Transport	Reference
2012	0.0020	0.0110	0.0042	1.05E-16	(HDIP, 2013, p. 84), (Ministry of Finance, 2014, p. [Table 14.1])
2030	0.0019	0.0104	0.0054	1.05E-16	(Planning Commission, 2010a, pp. 41-43).
2050	0.0019	0.0104	0.0073	1.05E-16	

9.3 Projected Demand

The electricity demand of the country is forecasted, using the above mentioned details. The values of which were found to be 430 TWh and 556 TWh in OG_Demand_Scenario and HG_Demand_Scenario respectively (Figure 9. 8). Further details of the forecasts can be found in Appendix-D of the thesis.

9.4 Regional Demand

In 2011, the NTDC (2011, pp. 140-149) published the electricity consumptions at a regional level (districts and DISCOs). Using the ratios of the consumption, the total forecasted demand of the country by 2050 was distributed among the regions. The relationship shown in eq. 9.1 presents a general form of the calculations.

$$D_R^F = \frac{D_R^C}{D_{Total}^C} * D_{Total}^F \dots\dots\dots\dots\dots\dots\dots\dots\dots eq.9.\ 1$$

$D_R^F = Region\ \mathrm{R}\ future\ energy\ demand$

$D_R^C = Region\ \mathrm{R}\ current\ energy\ demand$

$D_{Total}^C = Country\ total\ current\ energy\ demand$

$D_{Total}^F = Total\ projected\ future\ energy\ demand$

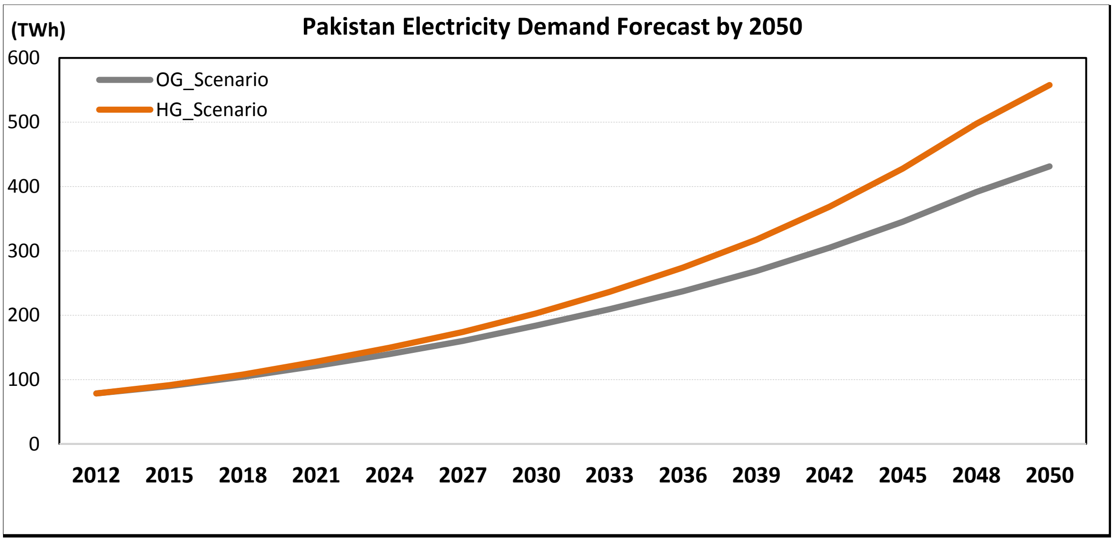

Figure 9. 8: Projected electricity demand of Pakistan by 2050 in the two demand scenarios (forecasts)

9.5 Load Curve

For hourly demand, the calculations' process used the 2007-08 load profile shown in Figure 9. 9 (NTDC, 2011, pp. 326-367). Distributing the demand across a year, the peak value of the demand was also assessed at the regional level, which is presented in TABLE 9. IV. It is important to mention that due to the unavailability of the regional profile, the overall system profile had to be assumed in all of them. In the case of using the regional profile, the most obvious impact will be on the import/exports of the regions. Since the regional pattern formed the system profile, the overall demand of the system will remain unchanged.

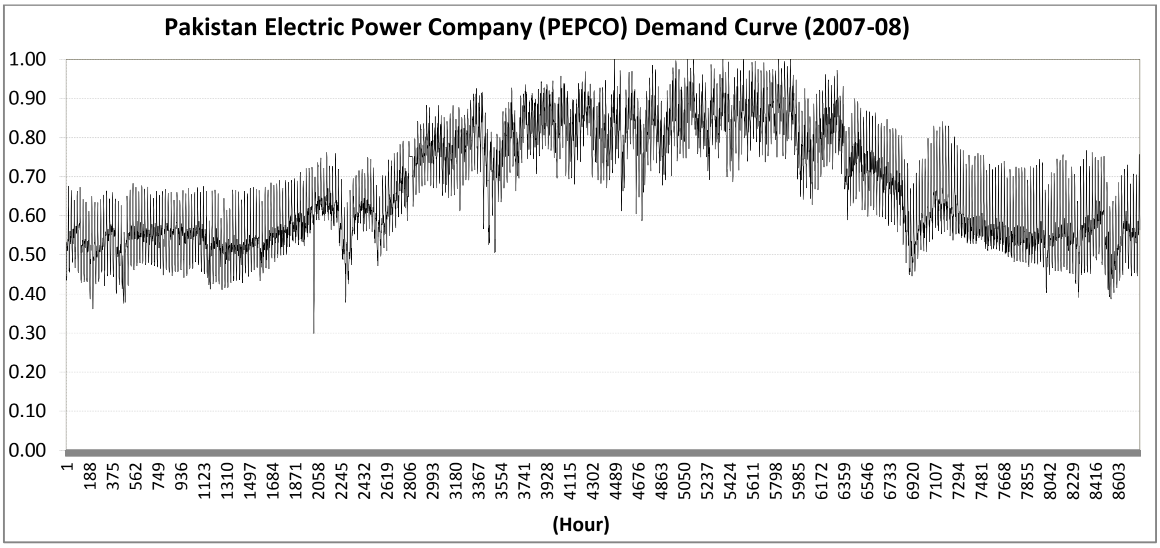

Figure 9. 9: Pakistan's power system normalized demand curve
Source: (NTDC, 2011, pp. 326-367)

TABLE 9. IV: Forecasted regional and total peak demand (MW)

Region	Base Year (2012)*	OG_Scenario		HG_Scenario		Base Year Reference
		2030	2050	2030	2050	
Gilgit	250	325	761	358	985	(H.A.Siddique, 2011)
AJ&K	500	649	1,522	716	1,969	(AJKHEB, n.d)
KP1	1,504	1,953	4,579	2,153	5,923	(NTDC, 2013b),
KP2	2,053	2,665	6,251	2,939	8,085	(NTDC, 2013b)
TESCO	785	1,019	2,390	1,124	3,091	(NTDC, 2013b)
IESCO	2,325	3,018	7,079	3,329	9,156	(NTDC, 2013b)
GEPCO	2,036	2,643	6,199	2,915	8,018	(NTDC, 2013b),
FESCO	2,747	3,566	8,364	3,933	10,818	(NTDC, 2013b)
LESCO	4,787	6,215	14,576	6,854	18,851	(NTDC, 2013b)
MEPCO	3,350	4,349	10,200	4,796	13,192	(NTDC, 2013b)
Baluch-1	640	831	1,949	916	2,520	(NTDC, 2013b) (PBS, 2014, p. [n.p])
Baluch-2	408	530	1,242	584	1,607	(NTDC, 2013b), (PBS, 2014, p. [n.p])
Baluch-3	194	252	591	278	764	(NTDC, 2013b), (PBS, 2014, p. [n.p])
Baluch-4	278	361	846	398	1,095	(NTDC, 2013b) (PBS, 2014, p. n.p)
SEPCO	968	1,257	2,947	1,386	3,812	(NTDC, 2013b)
HESCO	1,188	1,542	3,617	1,701	4,678	(NTDC, 2013b)
KESC	2,947	3,826	8,973	4,219	11,605	(NTDC, 2013b)
Total	**26,960**	**35,001**	**75,089**	**38,601**	**98,169**	

* The sum of the regional peaks is higher than the overall system peak. This indicates the difference in the timing of the peak demand in the regions.

9.6 Chapter Summary

The value of Pakistan's final electricity consumption was 76.7 TWh by the year 2012. With the addition of the unserved electricity in the domestic sector, the total demand was approximated to be 91 TWh. For the analysis of the system in 2050, the electricity demand of the country was forecasted using the approach of sectoral dis-aggregation. To incorporate future uncertainties, two scenarios of the economic growth have been considered for forecasting, with the average annual economic growths of 4.2% and 5.0%. The total demands in the scenarios were found to be 430 TWh and 556 TWh by 2050.

Chapter 10: Supply System Response and Behavior

The power system of Pakistan was simulated considering a renewable supply system and projected demand of 2050, with hourly temporal and regional (spatial) resolutions. This chapter presents the balances found and shows the supply system response, while fulfilling the demand. This chapter also elaborates the details of the balance found, in LW_Supply_Case and OG_Demand_Scenario, while the figures of the other cases are given as appendices of the thesis and in the attached CD (Compact Disk). Furthermore, detailed (i.e., hourly regional power imports/exports, etc.,) of all the simulations outputs and the findings are also available in the CD[110]. However, a summary of the important parameters of all the cases are presented in this chapter.

10.1 Supply System Cases

This section of the chapter refreshes the information of the supply cases. This information can be helpful while reading upcoming details. For simulation, two supply cases were considered in each demand scenario. The cases are termed as the LW_Supply_Case and the HW_Supply_Case (TABLE 10. I). In these cases, the capacity of the hydropower remained the same (i.e., 54.5 GW), while the capacity of the other resources changed. The wind capacities were 40% and 80% of the total potential in LW_Supply_Case and HW_Supply_Case respectively. For each case, the capacity of PV was found from the simulations, at different values of the system ENS and/or AUF.

Likewise, the simulations were performed considering several capacities of the PHES. Finally, the mentioned capacities at the two extreme values of the ENS were assessed to be appropriate ones. Generally, a higher PHES capacity helped in fulfilling demand, but the capacity needed additional generations (i.e., PV), to effectively operate. Consequently, the resources annual efficiency was reduced. The phenomenon of an increase in the excess generation with the generation capacity can be observed in the upcoming sections of the chapter. Similarly, the seasonal storage requirements were assessed exogenously[111] after use of the intermittent resources. The assumptions and findings of which are also described in the chapter.

10.1.1 PV Capacity Optimization

Pakistan's PV based generation potential is huge. However, the diurnal availability of the option and seasonal variations of the country's renewable resources resulted in substantial

[110] With the results, an explanatory note is added to briefly describe the contents of the CD. The description is helpful to explore the findings in details, which are presented in the thesis in a relatively summarized form due to their extra-ordinary size.
[111] Basic description is given in the "Analysis Methodology and Approach" chapter

TABLE 10. I: Supply system cases for simulation of the demand-supply balance with a renewable resources based power system in Pakistan by 2050

Supply Case	Simulation Point	Hydro (GW)	Wind (GW)	PV	Daily Storage (GW)*	Seasonal Storage (Biomass &Hydro)
LW_Supply _Case	LPC	54.5	45.9	Optimal (AUF>0.8)	4.4-7.8	As per requirements
	HPC	54.5	45.9	Optimal (0.8<AUF>0.6)	7.9-14.0	As per requirements
HW_Supply _Case	LPC	54.5	91.7	Optimal (AUF>0.8)	4.4-7.8	As per requirements
	HPC	54.5	91.7	Optimal (0.8<AUF>0.6)	7.9-14	As per requirements

***** The lower value is used in OG while higher value HG demand scenarios.

excess generations. It was, therefore, necessary to assess an appropriate capacity of the PV under different conditions. For this purpose, the approach used in the simulation process is described below.

Initially, a low capacity of the PV was considered in each supply case[112] and the system was simulated. The value of the system ENS, found by the simulation was checked. In the subsequent simulation, the PV capacity was altered as follows.

- If the demand existed (i.e. ENS > 0)[113], then the regional utilizations (i.e., AUFs) of the PV generated power were checked.
- The capacities increased rationally, according to the regional AUF e.g., an increment of a "100% capacity step" if the regional AUF was above 90%; similarly "90% capacity step" for the factor value between 80%-90%, and so on. The value of the capacity step was taken between 0.2 to 0.4 in most cases.
- The new capacities were used in the subsequent simulation and the ENS value was re-calculated and re-checked. The process repeated, until one of the following conditions was reached.
  - If the ENS value reached zero (i.e. demand fulfilled).
  - If an increase in the PV capacity was not effective in reducing the ENS value.

10.2 Supply System Response

The simulations of the demand-supply balance, considering incremental PV capacities, gave an insight to the system's behavior. For example, Figure 10. 1 presents the relevant parameters at different PV capacities in the LW_Supply_Case and OG_Demand_Scenario. In the figure, phenomenon regarding the supply system response can be observed, which are briefly explained in the following paragraphs.

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[112] If the value is too far from the optimum one, more simulations were required to achieve the desired value..

[113] Generally, If the ENS is zero in the initial simulation (les probable in case of Pakistan), it means the assumed capacities of the resources are most probably extra-ordinary relatively to the demand.

- An increment of the PV capacity helped in meeting the demand. However, the resource contribution decreased significantly beyond 55 GW. Consequently, the excess generation of the supply system grew relatively faster and the system overall efficiency was considerably reduced. This is due to a difference in the resources availability, particularly hydro and PV, across the span of a year.

  During the winter and early spring, the generations of the PV helped in meeting the demand and consequently, the simulation process continuously increased its capacity. However, during summer, the increase resulted in more generations than needed (i.e., excess generation). An additional increase of the PV capacity above 133 GW contributed almost exclusively to the excess generation, and the simulation process stopped.
- The transmission losses of the system decreased with an increase in the PV capacity. This occurred due to an increased in the PV generations, particularly in the central and southern parts of the country. Which facilitated the regions to use more local resources. Consequently, the inter-regional power flows and the transmission losses decreased. However, the excess generations helped in a relative more extensive operation of the PHES system. Consequently, the total thermal losses remain almost in the same range.
- By compromising the excess generation, the LW_Supply_Case can fulfill a demand up to 400 TWh, with a negligible support of the seasonal storage system[114]. It is important to mention that the support is of the energy, not the capacity because; the capacity requirements are based on the residual demand peaks[115]. In the HW_Supply_Case, this value was about 440-470 TWh.

In the figure, two extreme points of resource utilization are mentioned, i.e., the low PV capacity (LPC or low excess generation) and the high PV capacity (HPC or high excess generation). In each supply case, the system was re-simulated at the two points for detailed findings. The findings included the hourly demand-supply balance prior to the utilization of the seasonal storage.

Later, the seasonal storage was applied at the two points exogenously. In the next section, the approach of applying the seasonal storage and its findings in the LW_Supply_Case and the OG_Demand_Scenario are explained.

[114] The requirements of seasonal storage support are discussed in the coming section.
[115] The capacity requirements are discussed in the next chapter.

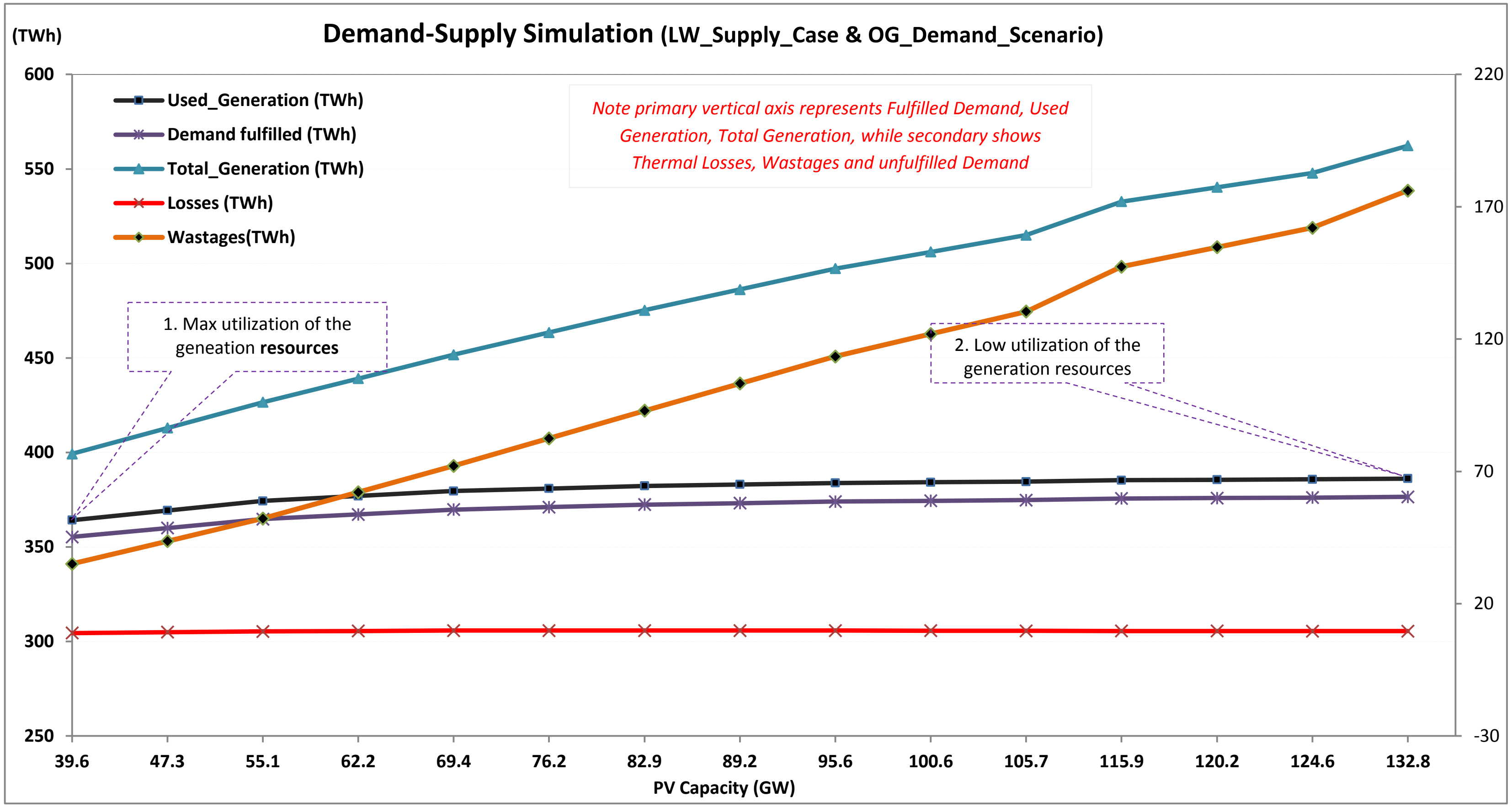


Figure 10. 1: Overall behavior of the system during simulation of the "OG_Demand_Scenario" and "LW_Supply_Case" (Findings)

10.3 Seasonal Storage Requirements

10.3.1 Residual Demand after Intermittent Resources Utilization

The system was re-simulated at the LPC and HPC for detailed analysis, as mentioned above. From the balances, the residual demands at the two PV capacities was found. The demand showed that the supply system, without seasonal storage system, mostly struggled during the winter and spring, in meeting the demand (Figure 10. 2). The figure shows the residual demands before applying the seasonal storage options at the LPC and HPC. To meet this demand, biomass and seasonal hydro storage system were considered as potential options. This approach and assumptions used in the case of the two supply options are discussed below.

10.3.2 Seasonal Storage Supply System

Biomass

Through observation of the residual demands, one can assess the requirements of the seasonal storage supply at the two PV capacities. The figures indicate the period, in which biomass utilization will be relatively efficient. The option was, therefore, applied in the periods with the following assumptions.

- Capacities of 16 and 14 GW were considered at the LPC and the HPC. The values were assessed by observing the residual demand.
- A ramping rate of 30% per hour was considered, to follow the load. The rate value of a typical sub-critical coal power plant is 5% per minute, which means that the assumption is quite conservative (NETL, 2012, p. 4).
- The minimum operational level, to avoid a cold start, was assumed to be 20% of the capacity. Generally, a typical sub-critical coal power plant can operate at 10%-50% of the capacity. The higher value is normally applied to control the emissions (NETL, 2012, p. 3).
- While applying the biomass generations, 1.2% transmission losses were assessed . The losses found from the demand-supply balance were in the range of 1.4% to 2.0%. Since the biomass generations are mostly required in the regions of its potential[116], therefore, a low value of the losses can be expected during the generated power transmission.

In Figure 10. 3, the biomass used at the two PV capacities can be seen. The figures show the annual hourly and 24-hour samples. From the samples, it is clear that the application of the

[116] Regional demand of biomass is discussed in the coming sections of the chapter.

biomass as an annual storage option contributed to the excess generation. This was obviously due to the assumed limitations.

A comparison of the two patterns shows that the resource utilization is more efficient at the LPC and needed less variation in the biomass generations. However, the requirements of the total generations at the point are more than the HPC, due to the difference of the total residual load.

Hydro-Based Seasonal Supply

The residual demand, after the biomass utilization, is assumed to be met by the seasonal hydro storage system. The demand can be obviously changed by adjusting the biomass capacity and maintaining a different level of biomass generation as a base-load supply. However, the decision will also affect the resource wastages, as discussed above. The values are, therefore, flexible and the final decision will depend upon the resources availability.

The residual demand after the biomass utilization is mostly in the period of low hydropower generation (Figure 10. 4)[117]. This makes a strong case for the development of the seasonal hydropower storage system, discussed earlier in the "Hydro Resource" chapter. By storing the extra water during summer, the unused capacity of the hydropower plants can be exploited during this period to generate power.

Finally, TABLE 10. II present a summary of the findings at the two points of the resources utilization in the LW_Supply_Case and the OG_Demand_Scenario. After utilization of the seasonal storage, a fraction of the demand still exists. This demand is assumed to be handled through demand management. At the two points, the capacity requirements of the seasonal storage system are not much different, but the total supply resources at the LPC are significantly higher than the HPC. Which means that the dependency of the supply system upon seasonal storage increased by decreasing the PV capacity, as mentioned earlier. Furthermore, the excess generation are almost double at the HPC than the LPC due to the high PV generations, particularly during summer.

TABLE 10. II: Summary of the biomass and Hydro resources utilization at LPC and HPC

Utilization Points	Residual Demand (TWh)	Biomass		Hydro Storage		Seasonal Storage Excess generation (TWh)	Managed Residual Demand (TWh)*
		Capacity (GW)	Energy (TWh)	Capacity (GW)	Energy (TWh)		
LPC_Point	58.97	16.0	62.15	14	14.8	3.62	0.39
HPC_Point	46.72	14.0	42.62	14	9.09	4.99	0.228

*Assumed to be managed i.e., load management, household sector storages etc.,

117 Hydropower generation profile can be seen in the figure "overall demand supply-balance" of the next section

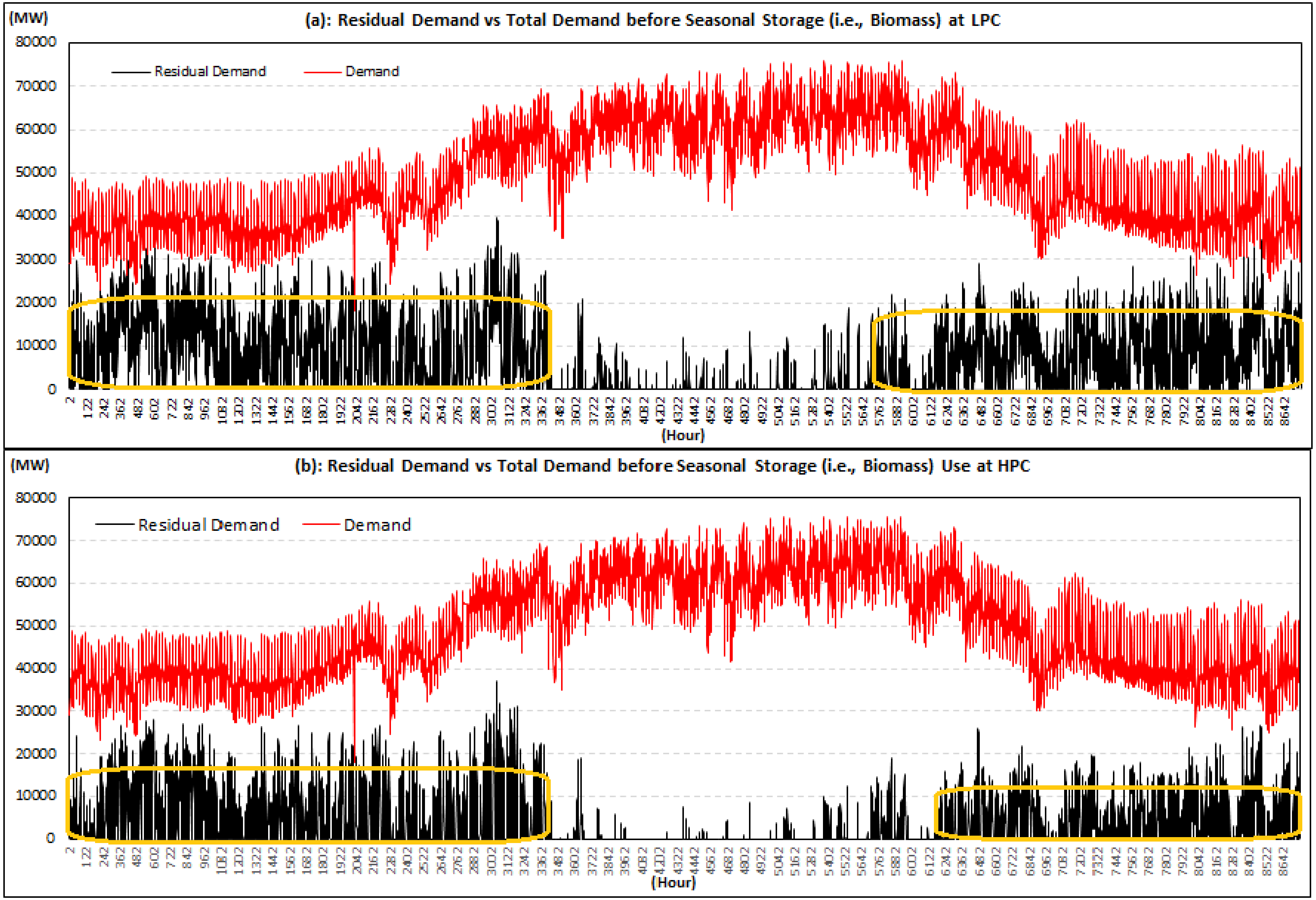


Figure 10. 2: Residual demand (a) at the LPC (b) at the HPC

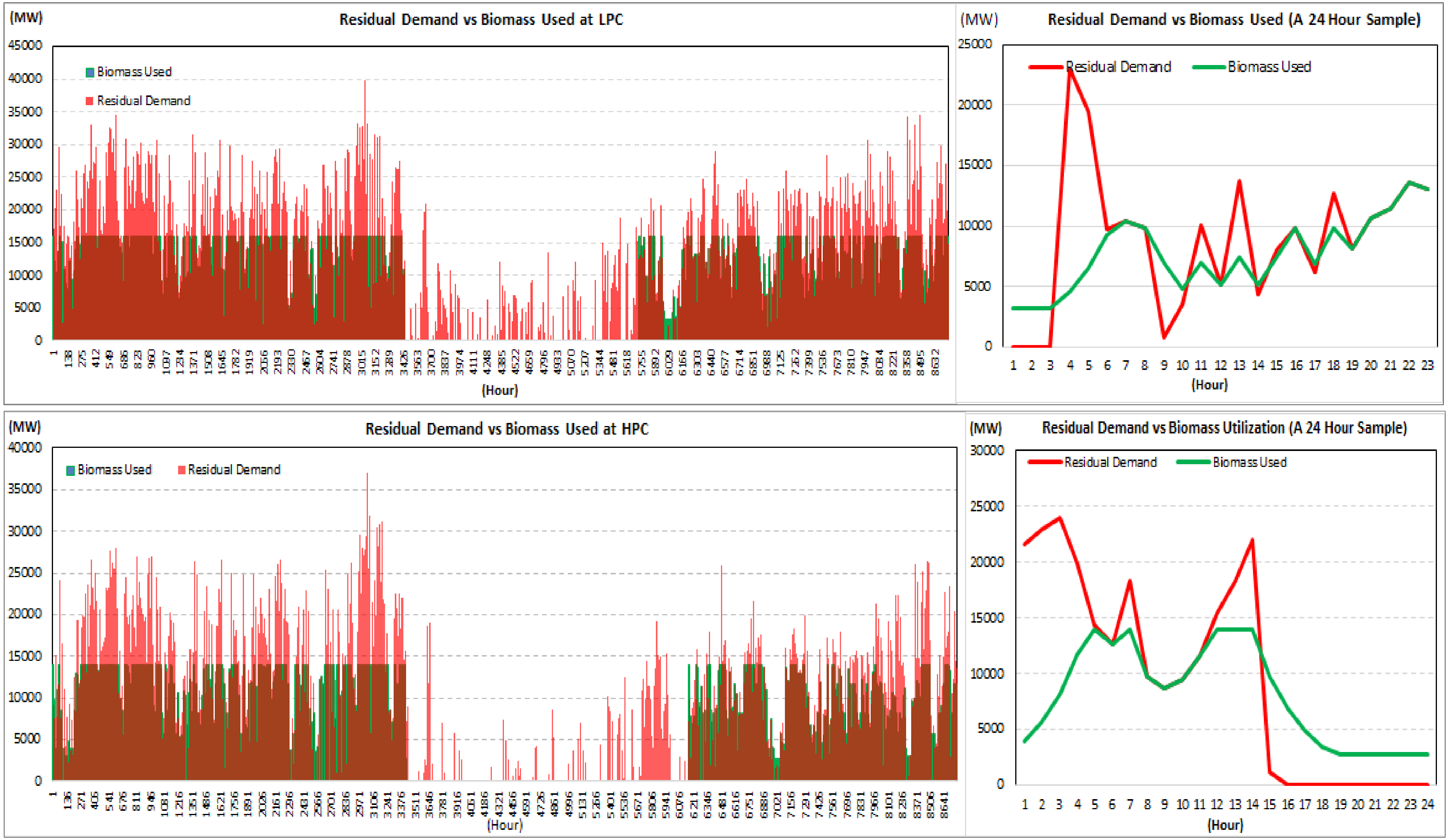


Figure 10. 3: Biomass utilization as Seasonal Storage (a) at the LPC (b) at the HPC (Simulation)

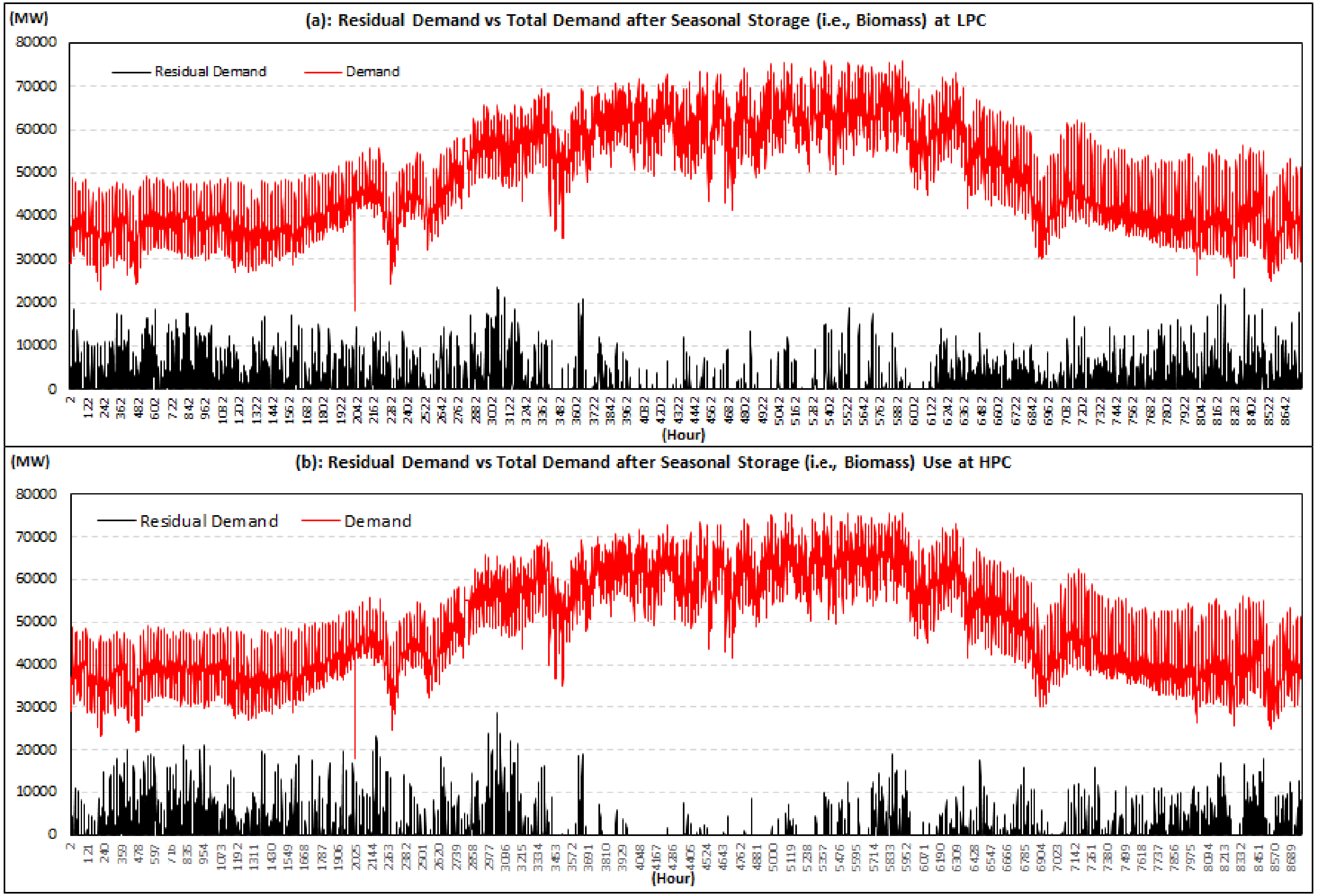


Figure 10. 4: Residual demand after utilization of the biomass resource (a) at the LPC (b) at the HPC (Simulation)

10.4 Demand-Supply Balance

The discussion of the previous section indicates that the supply system needed the seasonal storage system support for demand balancing and efficient operation. In this section, the overall demand-supply balances are presented. The balances elaborate the resources utilization and excess generation, across a single year. Generally, from an annual hourly balance, the system's overall trend can be assessed, but they are hard to be tracked.

For convenience, therefore, first the weekly balances (i.e., first week of January, April, July and October) at the LPC and the HPC are presented in Figure 10. 5 and Figure 10. 6, before the overall hourly balances. The figures of the other cases can be found in Appendix-F of the thesis. From the figures, the following points can be assessed.

- During winter and spring, the demand was lower. Still the supply system needed maximum support of the seasonal storage. The reason is obviously a low availability of the resources during the period (Figure 10. 5a).
- For an efficient operation, the system required relatively higher support of the seasonal storage supply. The requirements can be reduced by increasing PV capacity. However, the increment contributed to the excess generation, particularly during summer (Figure 10. 6b).
- During summer, the generations are so high that the supply system met the demand with almost no support of the PV generations and a negligible contribution of the PHES system. However, in the HG_Demand_Scenario, the system needed PV support, even during summer (see Appendix-F).

The figures also present a general reflection that an efficient operation depends not only on the resources combination, but also on the demand variations. This means that management of the load and consideration of a deferrable demand[118] can be effective to minimize the excess generation. This can also be achieved by considering a flexible component of the demand (e.g., storing electricity for transportation, conversion to fuel, etc.).

To assess the phenomenon across a year, Figure 10. 7 presents the annual hourly balances at the LPC and the HPC. The balances displayed substantial excess generations (i.e., wastages) during the period of high water flows. Therefore, if the seasonal storage required the pumping of water, the excess generation could be used for the purpose.

The weekly pattern of other cases can be found in Appendix-E, while the annual ones, in Appendix-F of the thesis.

[118] In this research, no such demand/load was considered e.g., conversion of electricity to gas, storing in hybrid cars etc.,.

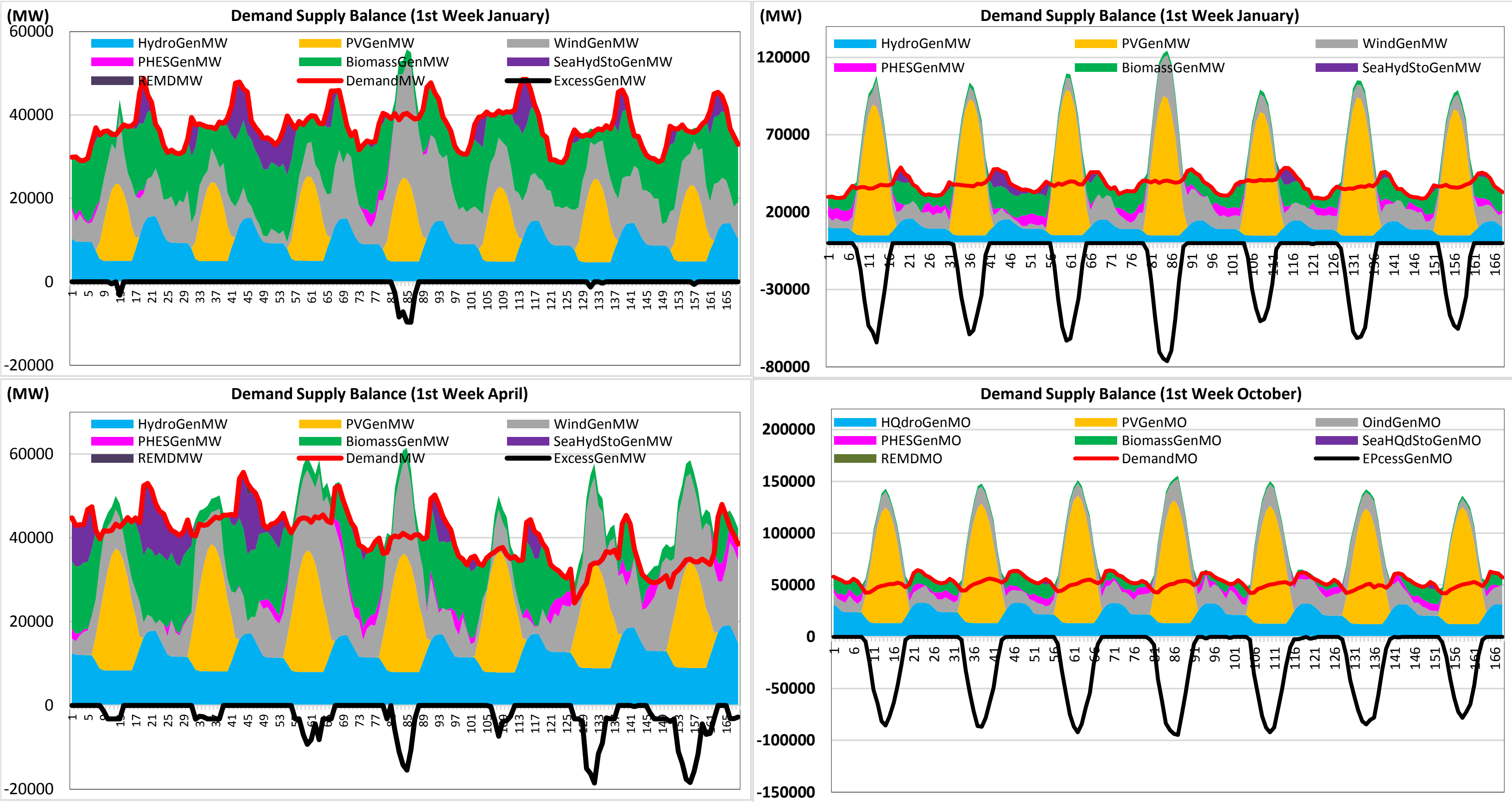


Figure 10. 5: Weekly demand-supply balances (a) at the LPC (b) at the HPC (Simulation findings)

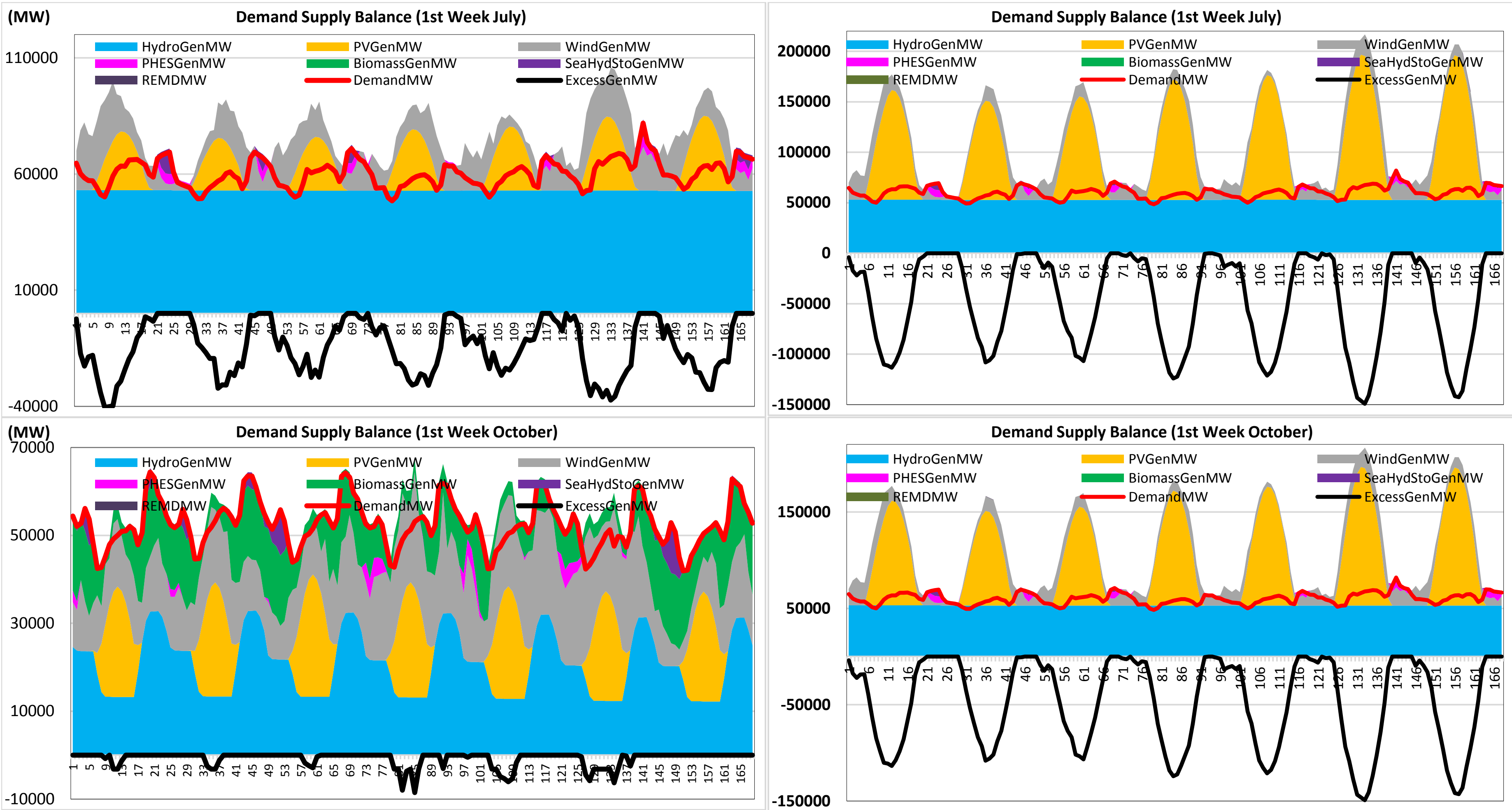


Figure 10. 6: Weekly demand-supply balances (a) at the LPC (b) at the HPC (Simulation findings)

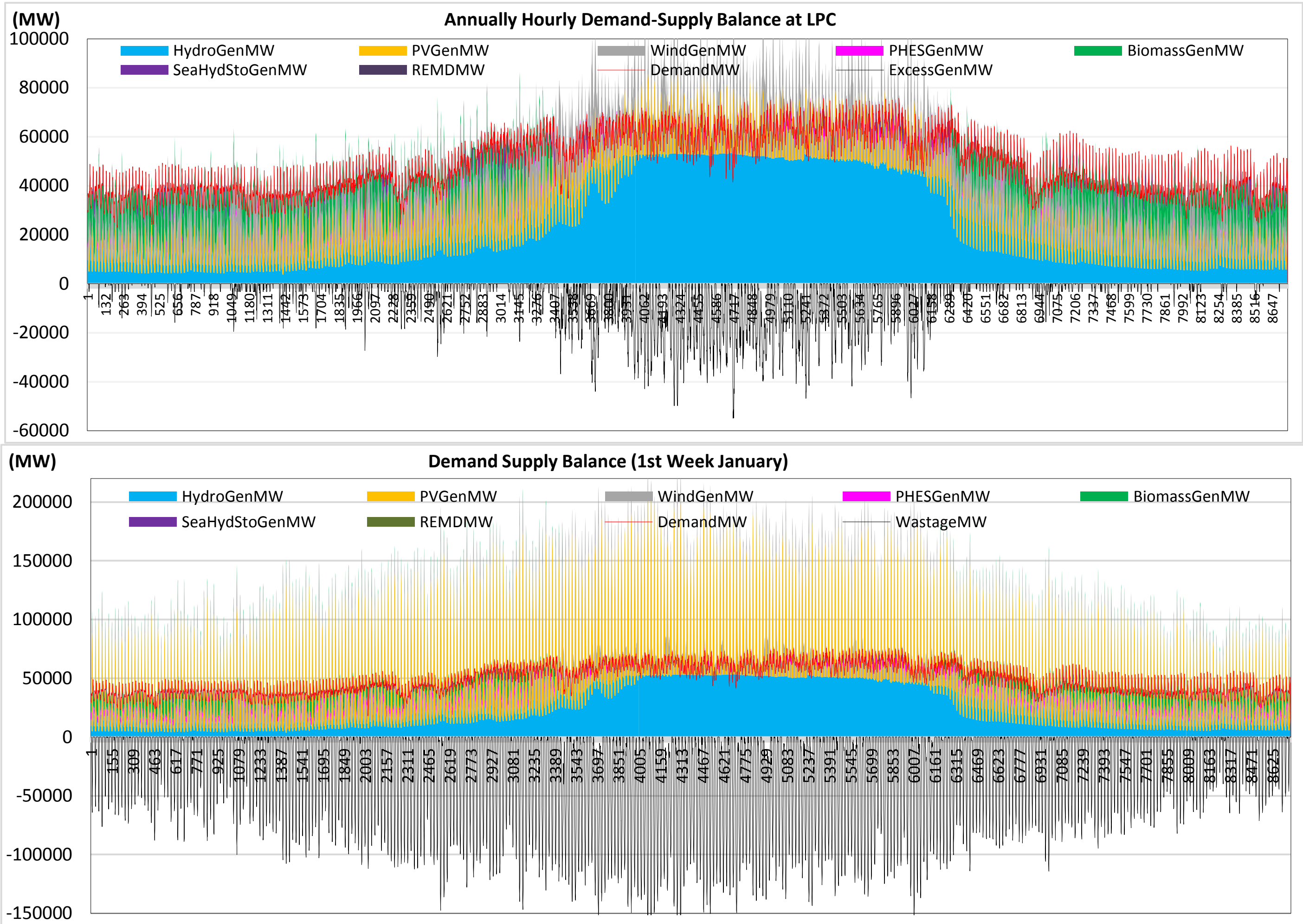


Figure 10. 7: Annual demand-supply hourly balance (a) at the LPC (b) at the HPC (Simulation findings)

10.5 Regional Demand-Supply Balance

10.5.1 Hourly Balances

The availability of the renewable resources and electricity demand substantially vary across Pakistan. Consequently, few of the regions fulfilled the total or a major part of their demands from local generations. Many even needed external support. In this section, the findings of the OG_Demand_Scenario and the LW_Supply_Case at the HPC are discussed to show the demand-supply condition at a regional level. Figure 10. 8 shows the one day monthly samples (i.e., 12 x 24 = 288 data points) of representative regions. The figures show local use, imports, seasonal storage utilization and exports of electricity usage. In this particular demand-supply case, the regions can be classified into five major categories, based on the aforementioned parameters. It is important to state that the categorization of the regions is flexible and can change with the supply resources and system demand. Furthermore, some of the regions may exhibit the characteristics of more than one category. This can be observed in the following description of the categories.

I. Seasonal Storage Supply and Import Dependent Regions: These are the regions which are highly dependent on imports (i.e., of intermittent supply resources) and require significant support of the seasonal storage system to meet their demand. They are located relatively far from the regions which have high hydro and PHES resources, and therefore, a limited supply of the resources are available there (Figure 10. 8a). LESCO, MEPCO, SEPCO, HESCO, IESCO and KESC are the regions, under the specific demand-supply conditions. In addition, Baluch-2, Baluch-4 and FESCO, also utilized a reasonable share of the seasonal storage supply. However, the regions are relatively less dependent on the imports of the intermittent resources.

II. Highly Import Dependent Regions: The only difference from the above one is that, they fulfill a major part of their own demand with a negligible support of the seasonal storage system (Figure 10. 8b). They are relatively closer to the regions, having significant extra generations of hydro and wind resources. This category can be comprised of TESCO, GEPCO and KP-2 among the seventeen regions.

III. Hydro and Wind Resources Enriched Regions: These are the regions, which fulfilled a major part of their demand from local resources. In addition, their contributions are significant and support the demands of the other regions. In them, KP-1, Gilgit and AJ&K are the ones that have substantial hydro and average wind resources, while Baluch-3, Baluch-4, HESCO have substantial wind resources. Figure 10. 8c presents the seasonal pattern of the type of regions.

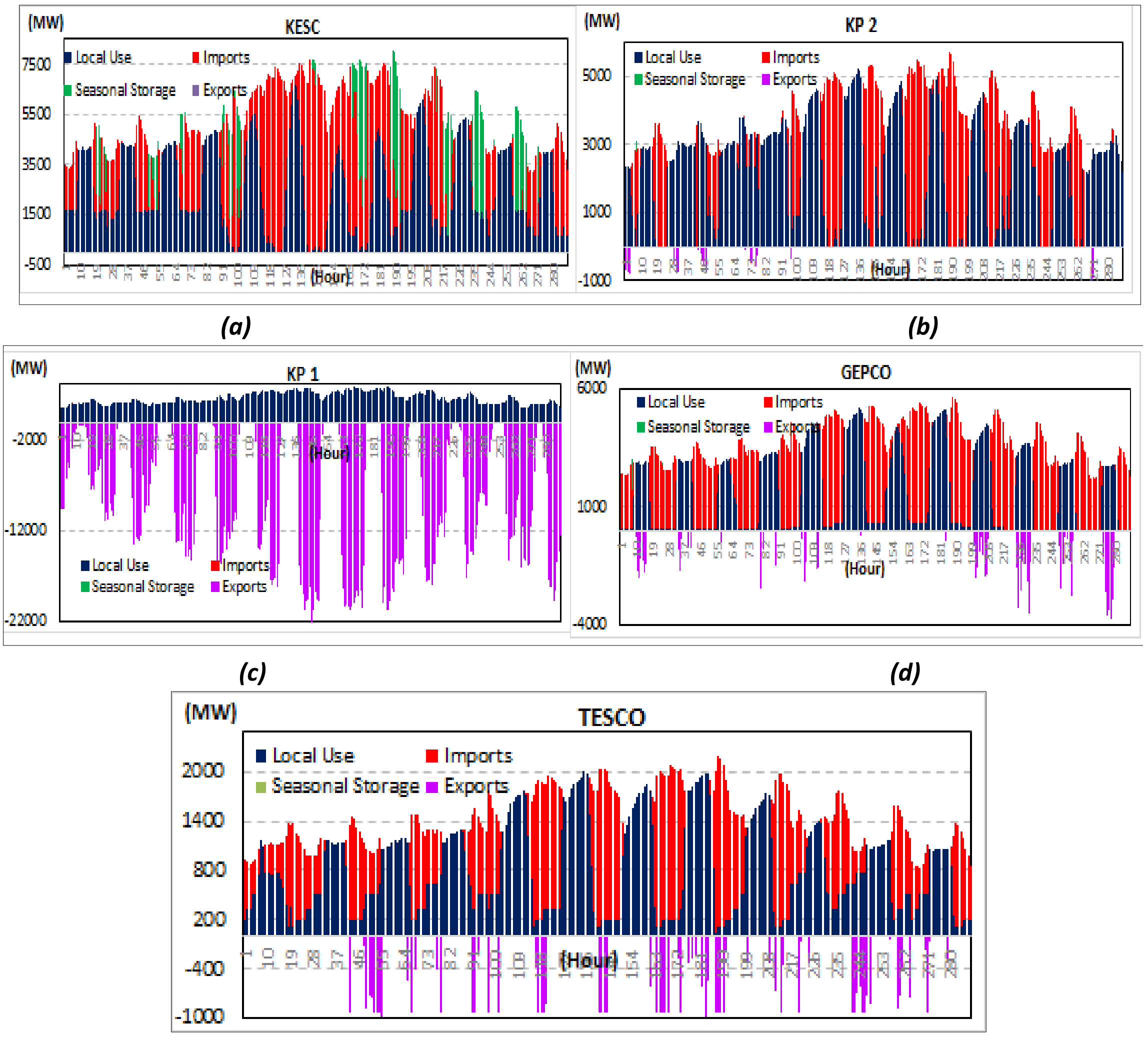


Figure 10. 8: One day monthly sample (i.e., total 288 observations) of: (a) regions highly dependent on seasonal storage supply and imports. (b) regions fulfilled major part of the demand through imports with insignificant contribution of seasonal storage supply. (c) regions having significant wind and hydro resources. (d) regions highly depends upon PV generation. (e) regions having limited own generations with PHES system

IV. Solar Resource Enriched Regions: These are the regions, which have limited or no wind and hydro resources. Consequently, the regions were highly dependent on the PV generations as a local source. They exported electricity during the daytime and imported it during the night (Figure 10. 8d). This phenomenon can be observed most obviously in the KP-2, GEPCO and TESCO regions.

V. Regions having PHES and Limited Generation Resources: This category is comprised of the AJK, TESCO and IESCO regions. In these regions, a special phenomenon can be observed during a low generation period. In these regions, the generations were reduced to such a level, that they needed external support in order to meet the demand and/or to support the PHES system pumping load. Later, the PHES stored energy was exported in the same hours as that of the imports. This phenomenon is actually due to the sequential process of calculations. According to the calculation approach, the supply resources (wind, PV, hydro) were utilized (including import-export) before storing by the PHES system. This could result in the imports by the regions, having PHES system, to meet their demand. Now, during the PHES operation (i.e., in the subsequent calculations), the region exported the stored energy during the hours of imports. It means that there will be only a net transfer of the electricity in either direction during the actual operation of the system.

Finally, the annual hourly balances of all the regions are presented in Figure 10. 9 to show the regional patterns of the balances. Since the temporal resolution of the figures is quite high, the dominating series overshadowed the others. For example, the phenomenon described above, in the point-V, cannot be observed any longer in the figures. To show the results in a more understandable way, an annual summary of each region is presented in the next section of the chapter.

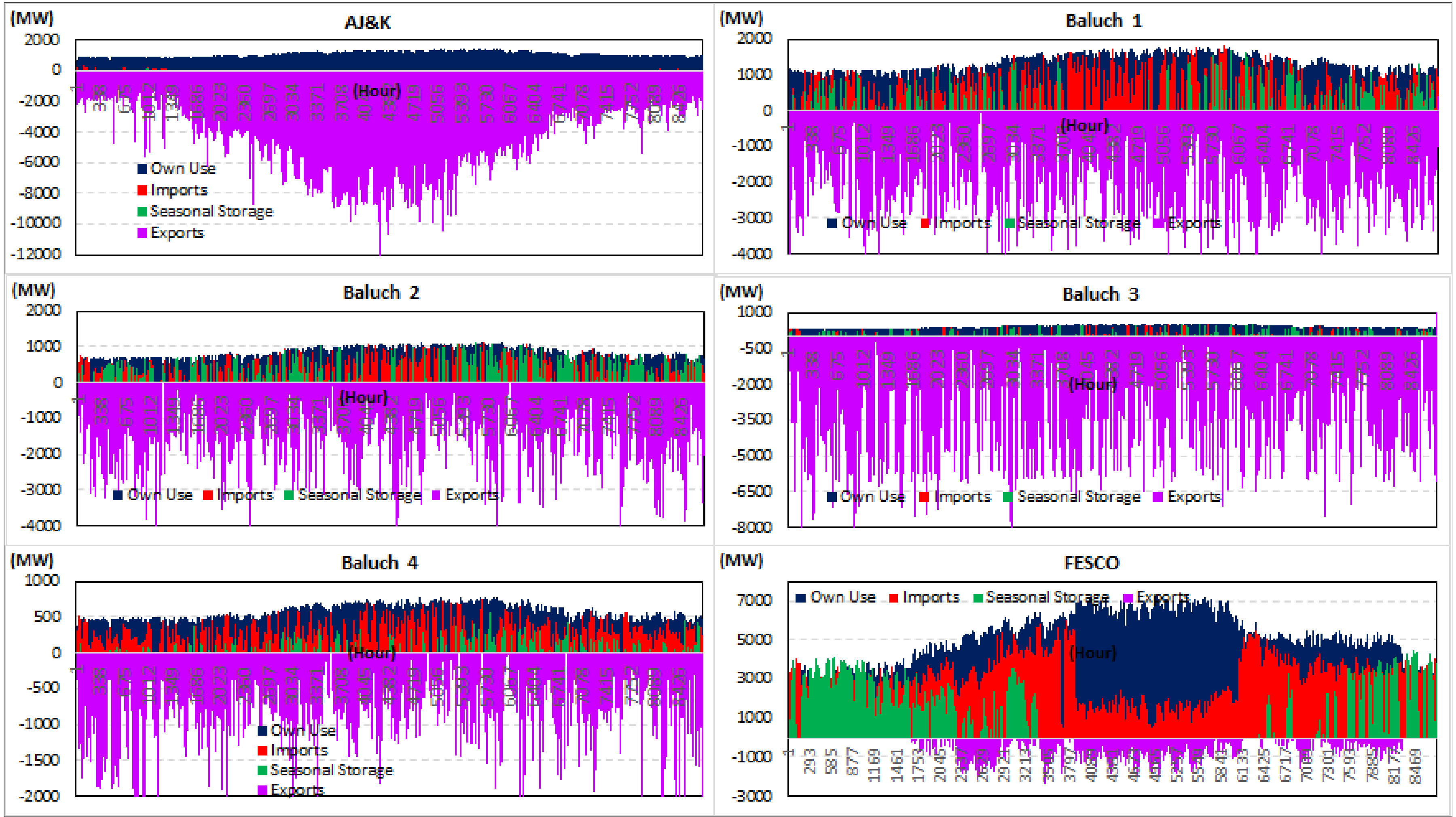


Figure 10.9 (a): Annual hourly profiles of resources utilization and exports in different regions in OG_Demand_Scenario and LW_HPC_Supply_Case

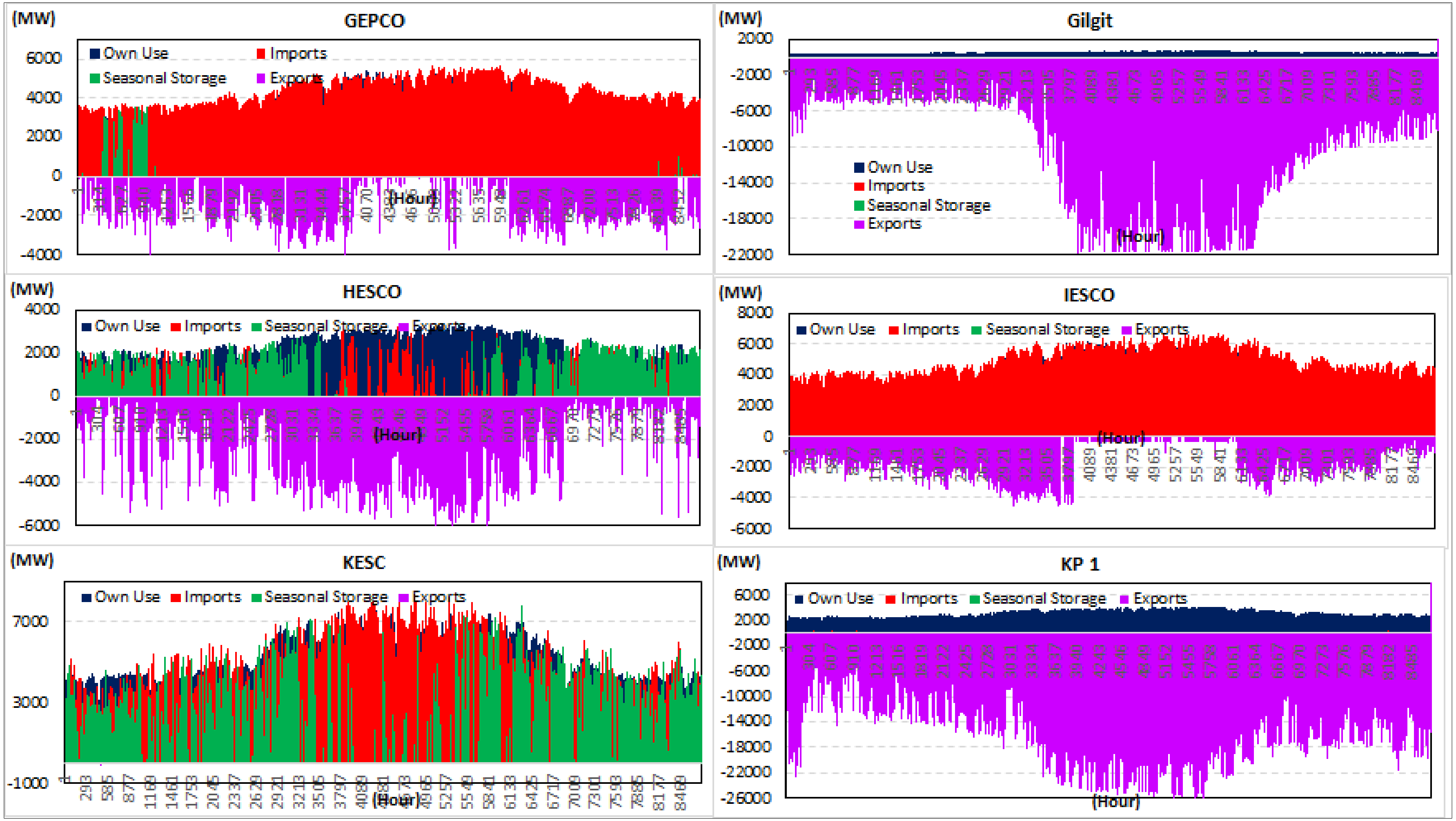


Figure 10.9 (b): Annual hourly profiles of resources utilization and exports in different regions in OG_Demand_Scenario and LW_HPC_Supply_Case (Simulation findings)

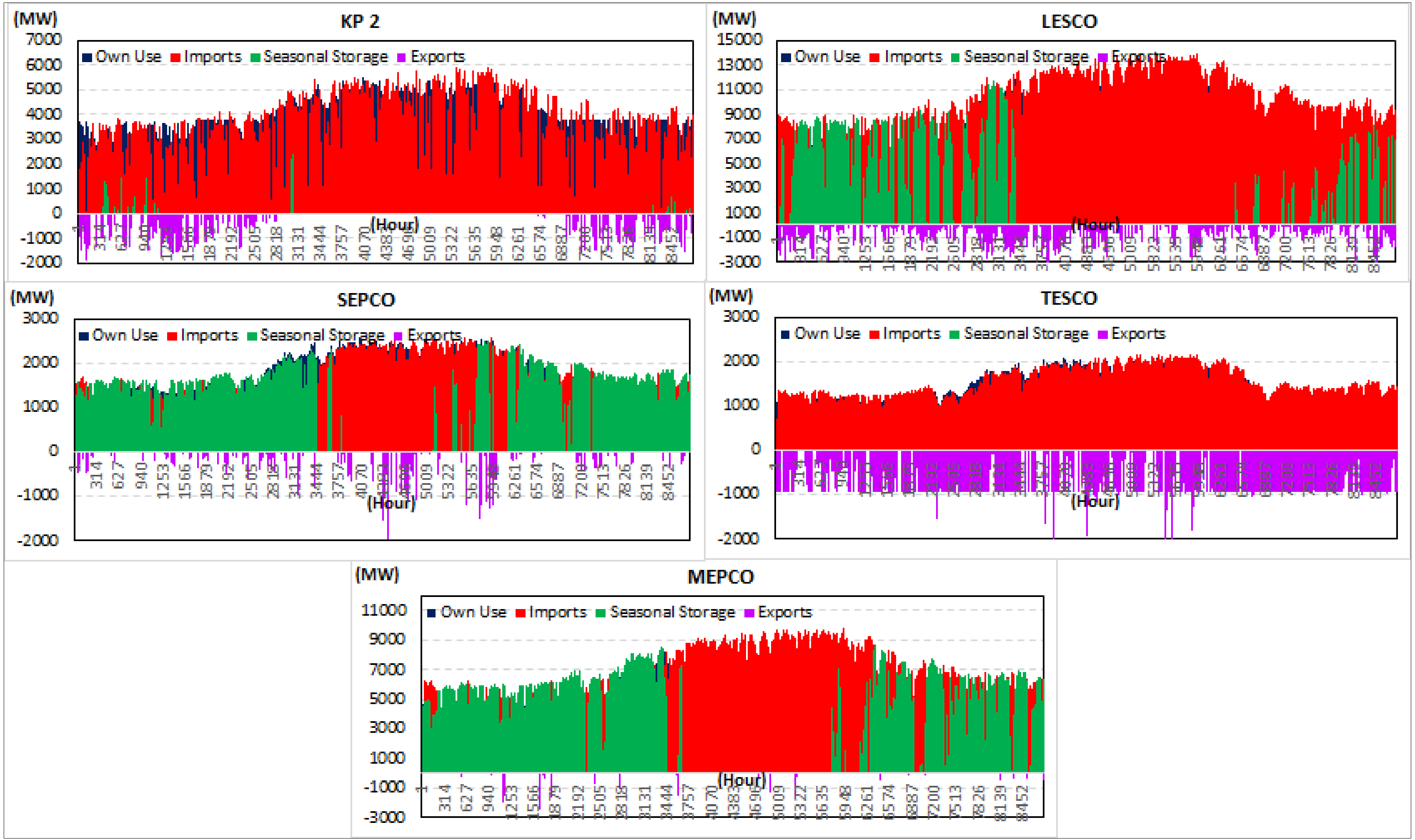


Figure 10. 9 (c): Annual hourly profiles of resources utilization and exports of different regions in OG_Demand_Scenario and LW_HPC_Supply_Case (Simulation findings)

10.5.2 Annual Regional Balances

In the previous section, the regional profiles are limited to highlight inter-regional dependency. The profiles became more undecipherable and unclear when the additional information of the inter-regional flows were included (a sample is given at the LPC in Appendix-G). To overcome this issue, the annual balances of the regions are presented in Figure 10. 10 at the LPC and the HPC, which gives a better idea of their dependency. The annual balance (Figure 10. 10) and hourly profile (Figure 10. 9) of a region can assist one, to conject the seasonal dependency of a region on the others. Furthermore, the tabular matrices of Figure 10. 10 and that of the other cases can be found in Appendix-H. The matrix contains the exact values of the electricity exchanged among regions. In the figure of the annual balances, one can observe the following points among others;

- From the annual balances (Figure 10. 10), it can be concluded that a major part of the northern areas (KP-1, Gilgit, AJ&K) exported electricity, was utilized by the central regions (IESCO, LESCO, GEPCO, KP-2). This signifies the importance of the northern areas hydropower as well as PHES potential. Furthermore, the balances can help to assess the seasonal dependency by observing the hourly import/export patterns in the context of the annual values.

  For example, the annual balance shows that KP-1 exported significant energy to TESCO and IESCO. Similarly, the annual balances of the two regions (i.e., TESCO, IESCO) show that their imports are mainly from KP-1. Therefore, the hourly profiles of the imports (Figure 10. 9) of TESCO and IESCO are obviously KP-1 exports. However, it is really hard to assess the seasonal inter-regional dependency in the case of regions like KESC, MEPCO, etc. Their imports consist of several regions' exports. Therefore, for them, the detailed results (i.e., in the attached CD) can be consulted[119].
- Likewise, the exported energy of the Baluchistan sub-regions was mainly utilized in the southern areas (KESC, HESCO, MEPCO).
- The balances show that a major part of the seasonal storage supply was needed in the regions (MEPCO, SEPCO, FESCO, LESCO, HESCO, KESC), where a high availability of agriculture residue can be expected (Figure 10. 11). In these regions, the only exception is KESC. However, the region is located in the neighborhood of HESCO and SEPCO, which contain a significant area of the agricultural activities, and will most probably produce enough biomass to fulfill the

[119] As mentioned earlier, a sample with regional values of import/export is given in Appendix-G. However, it is really hard to get an idea of exact seasonal inter-regional dependency. Therefore, it is highly recommended to look into the detailed results in the CD for the purpose.

KESC requirements. The overall scenario is, therefore, highly attractive for the utilization of biomass (crop residue) efficiently and with less transportation efforts.

- The inter-regional dependency of the system increased by increasing the resources utilization efficiency. This is obviously due to the relatively small generations of the PV resources in the central and southern parts of the country. In this situation, it is more likely that the system transmission infrastructures are high. However, at the same time, the system dependency on seasonal storage (i.e., biomass) also increased. Which will help to reduce the power transmission requirements i.e., due to more localized generation as discussed in the previous point.

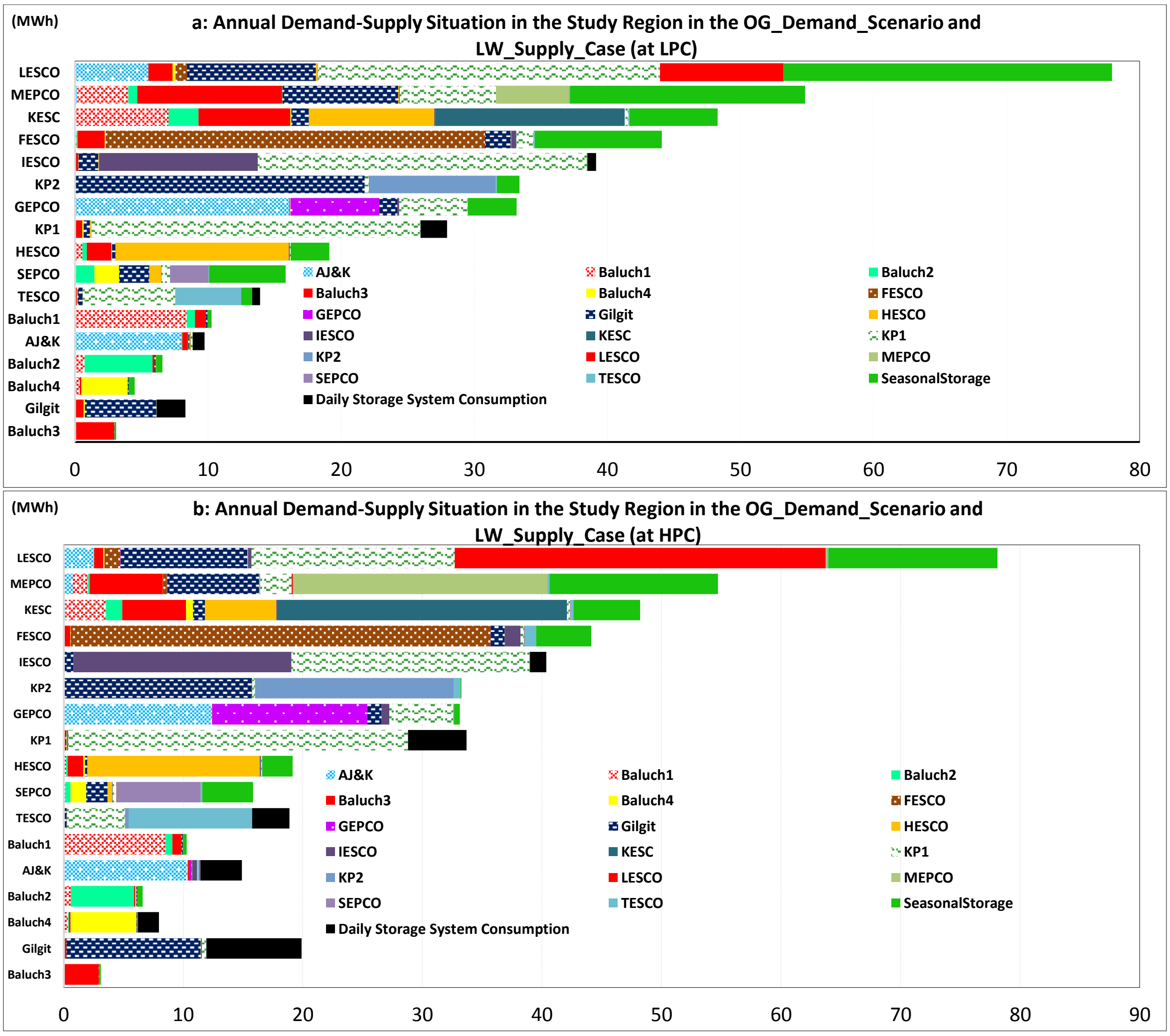


Figure 10. 10: Annual demand-supply balance of the regions (a) at LPC (b) at HPC (Simulation findings)

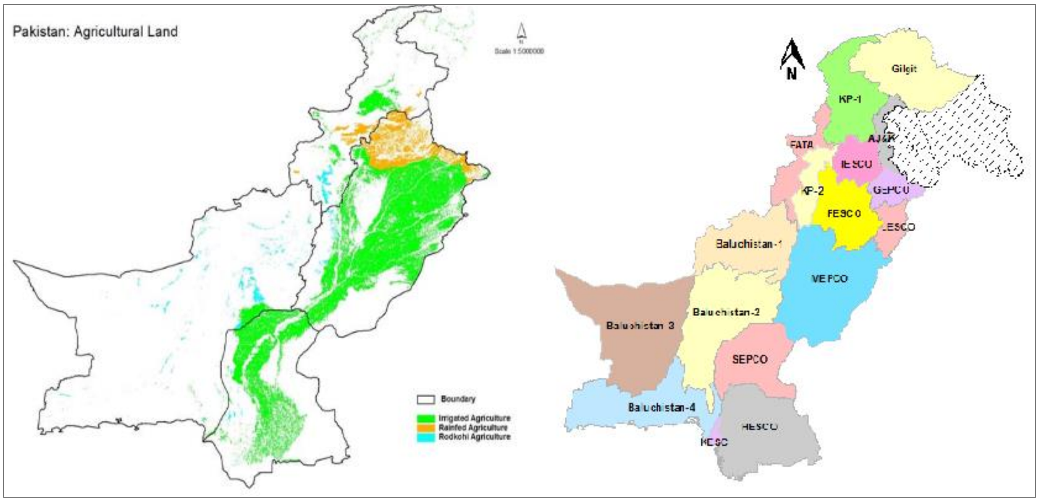


Figure 10. 11: Agriculture land in different study regions

Source: (Ministry of Environment, 2010, p. [Agriculture Land Use])

10.6 Supply Cases Summary

This section summarizes the supply cases in both demand scenarios to enable one for a comparison of the findings. The summary makes it convenient to assess the impact of the changes in the supply resources on the utilization, excess generation etc., with the change in the demand. The analysis of the findings showed that the contribution of all the three major resources (i.e., hydro, wind, solar) are important in meeting the demand. Since the capacity of the hydropower remained the same in all the cases, the impact of the wind and PV shares adjustment can be discussed.

The increase of the wind capacity significantly reduced the PV capacity requirements, particularly in the OG_Demand_Scenario. However, in this scenario, the increment resulted in extreme excess generation, even by reducing the PV contribution to a negligible level. It means that the use of the total wind resources in the case of the OG_Demand_Scenario, is less attractive than in the HG_Demand_Scenario. The decision turned out to be more important when an efficient system operation is desired. However, in the presence of high wind generations, the system needed less support (in a sense of energy, not capacity) of the PHES and seasonal storage systems.

In the HG_Demand_Scenario, a high wind capacity is relatively more efficient, as mentioned earlier. In this scenario, the high demand resulted in an efficient utilization of the resources, particularly during summer. Furthermore, the scenario needed the PV installation under all operational conditions, even if the system operated at the LPC.

For more information, TABLE 10. III contains a summary of the energy balances of the supply cases at the LPC and HPC, in the two demand scenarios.

10.7 General Discussion and Summary of the Findings

The analysis of the two demand scenarios with different supply cases revealed that the level of demand by 2050 can play an important role in shaping the proposed 100% renewable based supply system in Pakistan. If the demand is in the range of 400-450 TWh, the renewable resources can conveniently fulfill it. In a case of higher demand, the contribution of the PV, PHES and seasonal storage system will be important. However, compared to the PHES system, the impact of the seasonal storage system was found to be more convincing, due to significant variations in the supply resources and the demand, across a single year.

Based on the resources current assessment, a supply system having the PHES capacity of 4-8 GW and seasonal storage contribution of 5-13% (of the demand) can handle up to 430 TWh demand. The difference in the seasonal storage values reflects the share of the wind resources and the excess generation level e.g., the lower value means the case of high wind capacity with high excess generation.

Similarly, a further increase of the demand will require more support from the seasonal storage, as well as from the PHES system. For example, in the HG_Demand_Scenario (i.e., 556 TWh), the seasonal storage requirements were approximately 7-20% of the demand. This means that the requirements increased by a factor of almost 1.5 as compared to the one needed at 430 TWh.

A further increase in the demand will require more support of the resources, but the excess generation due to the use of biomass or limitation of the resources (i.e., biomass) availability can rise as a challenge. In that case, an increase in the PHES and compromise on the excess generation or use of the excess generation to serve a flexible load, will be a possible option. Another alternative option can be the use of a technology based storage system, but that decision will depend upon the future development of the technologies.

From this discussion, it can also be concluded that improvements in the system's efficiency can be disregarded up to a demand value, at which the seasonal storage requirements are not extraordinary. Beyond that, a tradeoff between the efficiency improvements and development of the additional resources will exist. In short, several factors, including: the future demand, total generations, storage technology costs and their development, can affect the final combination of the resources.

TABLE 10. III: Summary of the resources utilization and excess generation of the system in the two demand scenarios and all the cases at LPC and HPC

Demand Scenario	Supply Case	Demand (TWh)	Hydro (TWh)	Wind (TWh)	PV (TWh)	Daily Storage (TWh)	Biomass (SS, TWh)	Hydro (SS, TWh)	Thermal Losses (TWh)*	Res. Dem. to be Managed (%)	Excess generation (TWh)
OG_Scenario	LW_LPC_Case	430.1	213.4	116.1	97.0	8.2	56.9	13.2	8.9	0.09%	38.7
	LW_HPC_Case	430.1	213.4	116.1	282.9	20.2	39.1	13.7	11.5	0.05%	255.8
	HW_LPC_Case	430.1	213.3	232.3	12.7	6.6	47.1	7.7	10.9	0.08%	72.7
	HW_HPC_Case	430.1	213.3	232.3	147.7	16.6	23.8	4.8	12.5	0.07%	179.7
HG_Scenario	LW_LPC_Case	556.6	213.4	116.2	168.3	20.8	110.8	24.7	14.38	0.07%	62.7
	LW_HPC_Case	556.6	213.4	116.2	386.8	48.7	70.0	25.6	19.77	0.21%	236.6
	HW_LPC_Case	556.6	213.3	232.3	108.7	19.1	67.8	17.4	15.64	0.19%	68.5
	HW_HPC_Case	556.6	213.3	232.3	345.4	41.6	38.9	11.0	20.56	0.15%	270.7

LW_LPC= Low Wind Low PV Capacity; LW_HPC=Low Wind High PV Capacity ; HW_LPC=High Wind Low PV Capacity ; HW_HPC= High Wind High PV Capacity;; SS=Seasonal Storage
**The thermal losses included both transmission as well as PHES operation losses*

Chapter 11 System Infrastructure and Cost Assessment

This chapter discusses the capacity and transmission requirements of a renewable electric power system in Pakistan by 2050. The capacity requirements were assessed from the simulation of the demand-supply balances, as discussed before in the thesis. The simulation also helped in finding the inter-regional power flows. From which, the transmission system requirements were estimated using the approach described in the “Analysis Methodology and Approach” chapter.

The findings are presented in two different sections, for convenience. The first section describes the requirements of the installed capacity, while the second one of the transmission system.

11.1 Generation System Installed Capacity

The supply cases were analyzed considering two extreme values of the PV capacities (i.e., LPC and HPC), as discussed in the previous chapter. A summary of the capacities requirements assessed from the simulations is presented in TABLE 11. I. From the capacities requirements, one can assess the system response by observing the following points, among others.

- OG_Demand_Scenario: Change in PV capacity vs. change in wind capacity at the HPC:

  In the OG_Demand_Scenario, the difference in the PV capacity of the two supply cases at the HPC is 76 GW, compare to the 45 GW increase of the wind. In fact, at the HPC, PV generations were effectively used by the system in the LW_Supply_Case. While in HW_Supply_Case, the high excess generation (due to high wind capacity) forced the system to reach the AUF limit (i.e., 50%-60%) relatively soon. Consequently, the difference in the PV of the two supply cases is very high.

- OG_Demand_Scenario: Change in PV capacity vs. change in wind capacity at the LPC:

  At the LPC, the HW_Supply_Case allowed almost no PV capacity, again due to the high wind excess generation, which forced the supply system to reach the AUF limit straightaway. Similarly, compared to the HPC, there was a smaller margin of excess generation for the LW_Supply_Case at the LPC. Therefore, the AUF limit (>80%) reached relatively soon. Consequently, the difference in the PV capacity of the two cases at the LPC is just 47.8 GW i.e., less than the wind capacity increase.

- HG_Demand_Scenario: Change in PV capacity vs. change in wind capacity:

  In the HG_Demand_Scenario, this difference at the HPC and LPC was reduced, due to a relatively efficient utilization of the wind resources. The utilization maintained a high AUF for a long enough time, and allowed for a significant PV addition. Therefore, the differences in the PV capacities of two supply cases were just 21 and 33.6 GW.

- The reduction in the required capacity of the seasonal storage system (i.e., the sum of the biomass and seasonal hydro storage capacities) can be confirmed from the figures with an increase in the capacity either PV or wind or both. This means that the increase of the resources not only reduced the total residual demand but also its peaks.
- A comparison of the two cases shows that the impact of the intermittent resources (i.e., PV and wind) total capacity increment[120] on the seasonal storage capacity is more obvious. This means that, although a high installation of the intermittent resources can help the supply system, a tradeoff can still be made between the resources installation and seasonal storage requirements.

For an efficient operation, approximately 30%-50% (35-55 GW) of the installed capacity of the wind resources, looks reasonable at 400-450 TWh. Above this demand, the system will be able to utilize a relatively high wind capacity more efficiently. Similarly, the PV capacity can be adjusted as per conditions e.g., allowed limit of the excess generation, PHES installed capacity, etc. The values in the table are, therefore, indicative reference values at the two extreme points of system operation i.e., LPC and HPC.

[120] i.e., This can be observed, by comparing the seasonal storage requirement of the HW_Supply_Case at the HPC with other supply cases in both demand scenario.

TABLE 11. I: Installed capacities requirements in OG and HG Demand Scenarios

Demand Scenario	Supply Case	Peak Demand (GW)	Hydro (GW)	Wind (GW)	PV (GW)	Daily Storage (GW)	Biomass (SS*, GW)	Hydro (SS, GW)
OG_Demand_Scenario	LW_LPC_Supply_Case	75.7	54.5	45.8	55.1	4.4	16.0	14.0
	LW_HPC_Supply_Case	75.7	54.5	45.8	161.7	7.9	14.0	12.0
	HW_LPC_Supply_Case	75.7	54.5	91.70	7.3	4.4	16.0	12.0
	HW_HPC_Supply_Case	75.7	54.5	91.7	85.4	7.9	12.0	12.0
HG_Demand_Scenario	LW_LPC_Supply_Case	98.0	54.5	45.8	94.9	7.8	22.0	22.0
	LW_HPC_Supply_Case	98.0	54.5	45.8	220.0	14.0	21.0	20.0
	HW_LPC_Supply_Case	98.0	54.5	91.70	61.3	7.8	20.0	19.0
	HW_HPC_Supply_Case	98.0	54.5	91.7	198.9	14.0	18.0	16.0

*SS=Seasonal Storage

11.2 Transmission System

11.2.1Existing Infrastructure

Pakistan’s transmission system consists of several corridors (Figure 11. 1) (NEPRA, 2014b, p. 21). It integrates the load centers to the fossil fuel based power generation facilities in the south, and hydropower plants in the north. The lines of 132 kV and below[121] are managed by the distribution companies (i.e. DISCOS), and the NTDC operates and maintains the system of 220 kV and above voltage (i.e., currently exist only 500 kV). The NTDC system consists of twelve 500 kV and twenty-nine 220 kV grid stations. To accommodate future power flows, the company has planned to introduce a higher level (i.e., 765 kV) and a direct current (DC) power transmission technology in the grid system (NTDC, [n.d], p. [online]).

11.2.2 Future Perspective

Pakistan’s hydropower resources are under development. To utilize the resources, an expansion of the transmission system toward the northern areas is mandatory. Similarly, the existing lines between the southern and central regions of Pakistan also remain under stress, which sometime results in partial/full blackouts of the system. To overcome this problem, a strengthening of the lines is among the future targets of the NTDC, and can be found in the current development program of the company (ADB, 2015, p. 5).

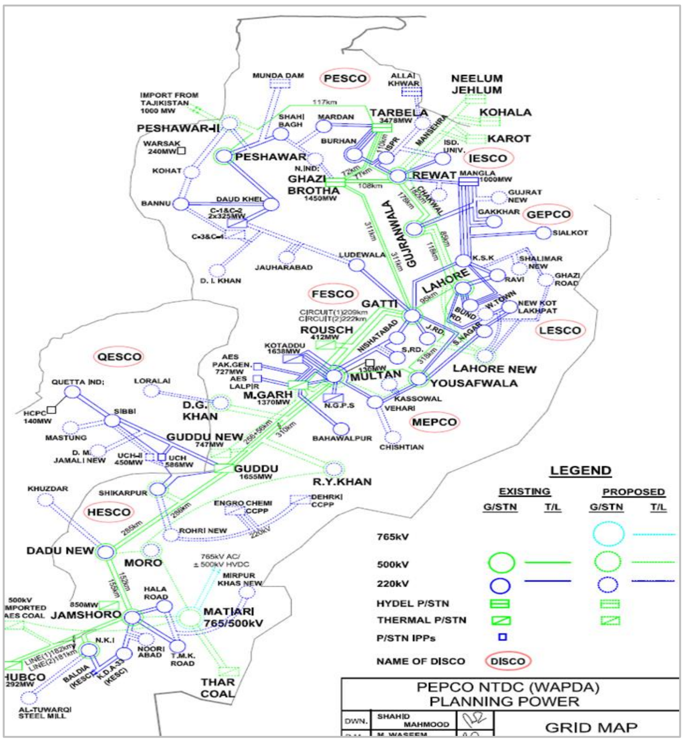


Figure 11. 1: Existing Power Transmission System in Pakistan (NEPRA, 2014b, p. 21)

[121] The below level are 66 kV, 33 kV, 11 kV, 400 V and 220 V

This means that the system will expand most obviously to accommodate the future requirements, and the development of a renewable based supply system will not need an extraordinary expansion. However, the existing corridors capacity will be several times higher than the current ones in order to operate the system.

The most obvious additional infrastructure will be required in the southwest, to connect the regions to the national grid system. In that case, the system layout will be most likely as shown in Figure 11. 2. For the infrastructure assessment and analysis, the same layout has been considered in the research[122].

11.3 Transmission System Analysis

In a transmission system, power flows through a line (i.e. segment of the system) can be very different from other lines. Normally, lines integrating outside regions with limited generation resources transmit less power than centralized lines. To accommodate this concept, the transmission lines have been divided into segments (Figure 11. 2), and the calculations were performed for each of them according to the power flows.

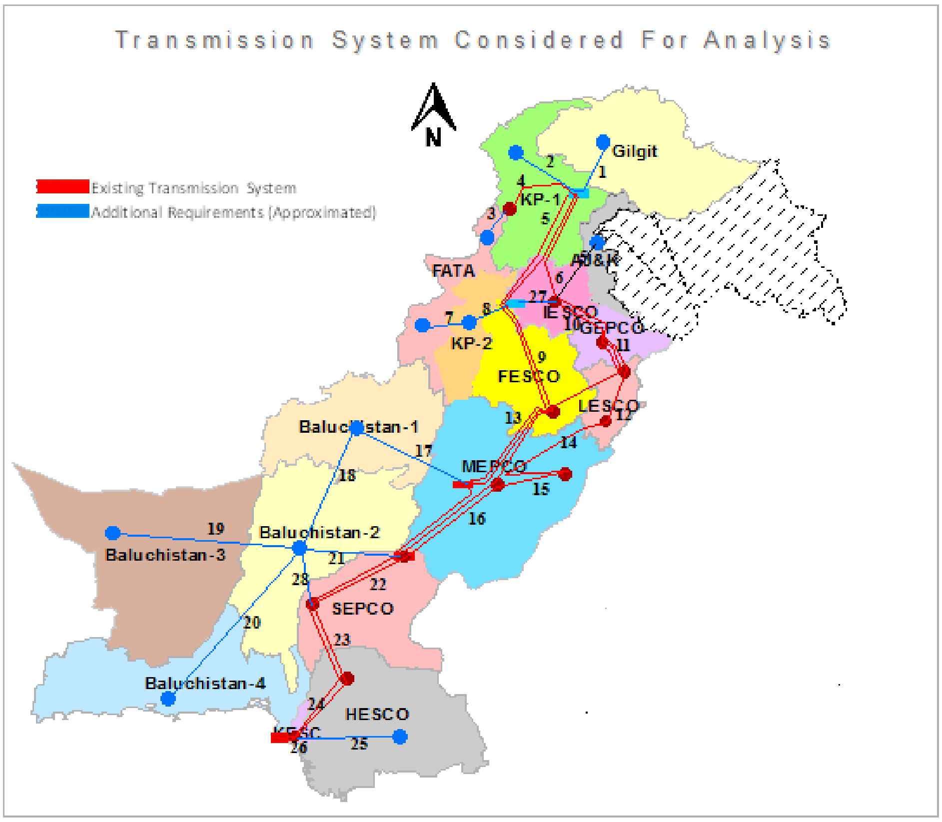


Figure 11. 2: Pakistan's transmission system layout, regenerated from (NEPRA, 2014b, p. 21) with the assumptions of the additional lines

[122] The techniques and methodology used for the analysis are described in the Methodology and approach chapter.

Similarly, the load-ability of a transmission line depends upon the length, voltage, and phases geometry of a line (discussed in chapter 03). The NTDC map seen in Figure 11. 1, shows the lengths of the existing lines in an actual layout, which are re-sketched (Figure 11. 2) with the expected future lines. Using the two maps, a relationship between the actual length and a representative line was estimated. This helped in the approximation of the future's lines lengths.

11.4 Transmission System Infrastructure Requirements

The optimization of a transmission system depends upon the system's specific conditions. For example, a single 500 kV line can transmit an electric power load with less congestion than two 220 kV lines. For installation, beside economics, factors like, land availability, system reliability, environmental impacts, etc., can influence the selection (AESO, 2013, pp. 31-34). It is beyond the scope of the work to assess the optimal conditions at the corridors of the system. For calculations, therefore, a general rule was applied. The rule was: if the number of required lines exceeds 05, switch to a higher level of voltage. With the rule and methodology[123], the transmission system infrastructure requirements of each supply case were calculated (TABLE 11. II).

In general, lines of two different voltage levels with the same length, cannot be regarded as identical for power flows, therefore, the total infrastructure requirements are expressed in the kV-km unit instead of km for a comparison.

The infrastructure requirements shows that both the inter-regional flows (i.e., MVA values) and the transmission system requirements are higher at the LPC than at the HPC, under all supply conditions. This means that the low generations at the LPC forced the regions to be more dependent on one another, as was seen in the previous chapter. Consequently, more power flows occurred across the system.

It is important to mention that the values given ignored the impacts of the seasonal storage for two reasons. First, it is assumed that a high share of the seasonal storage generation will be localized by using biomass resources (Figure 10. 11 of the previous chapter). Second, the seasonal storage supply was needed during the periods, when the overall demand was low. In that case, it is less probable that the lines will be congested than at the demand level.

A comparison of the two supply cases in the OG_Demand_Scenario, shows that the lines requirements of the two supply cases are not very much different. The reason is that there are higher local generations relative to the system demand. However, in this situation, the

[123] Describe in the chapter 03.

LW_Supply_Case is more dependent on the seasonal storage supply. If the system is forced to reduce this dependency through an increase of the PV and PHES capacities, the requirements of the transmission system infrastructure will be definitely high. In the demand scenario, the most effective reduction in the transmission capacity requirements was observed in the high wind and high PV supply case. The reason is obviously, as the high local generations in the central and southern regions significantly reduced the power import/export among the regions.

In the HG_Demand_Scenario, the relatively high demand reduced the availability of the extra wind and hydropower generations in the LW_Supply_Case. Consequently, the case has a maximum PV generations dependency, which were locally available in most of the regions. However, the excess generation phenomenon limited the PV installations, and again, the system needed the highest support available from the seasonal storage among all the cases. This means that the system's infrastructure will definitely increase in this case, if the seasonal storage options (biomass) are inadequate.

In the HG_Demand_Scenario, the increase of the wind resources made it possible, particularly in the southern regions, to export relatively more wind power to the nearby and more centralized parts. Consequently, the system transmission requirements slightly increased to accommodate the flows.

In general, it was found that an efficient operation of the system (i.e., at the LPC) needed higher transmission system capacity than in the case of allowing high excess generation (i.e., at the HPC), regardless of the demand. This is obviously due to more inter-regional flows at a relatively low generation level. However, the transmission line requirements in the northern areas slightly increased at the HPC to support the operation of the storage (i.e., PHES) system.

From the results in the table (TABLE 11. II), it can also be concluded that an increase in the demand will definitely increase the infrastructure requirement. However, the argument needed additional information from a biomass dependency example. For example, in the table, the difference in the infrastructure requirements of the two demand scenarios is negligible. To understand the reason for this, it is required to look into the share of the seasonal storage supply system i.e., more dependency on the biomass (seasonal storage) will most probably reduce the infrastructure requirements.

Finally, from the analysis, it can be found that the maximum expansion/strengthening of the system will be required in the northern part of the country. In Figure 11. 2, the transmission lines located in the adjacent Gilgit and KP-1 regions, run all the way up to the LESCO region, will require an extra-ordinary infrastructure in order to support the power flows of 42-50 GW. This expansion is highly driven by the hydropower and the PHES resources in the north. In the southern regions, the maximum expansion was found at the transmission line from the Baluch-3 region, to its grid integration point. This segment will require the support of a power flow in the range of 5GW-12GW in the supply cases. Furthermore, a noticeable expansion will be required of the line between the SEPCO and MEPCO region. For more information, the findings of all the cases is given in Appendix-I, to see the details of the maximum flows and lines requirements at the segment level.

TABLE 11. II: Transmission System Infrastructure Requirements for 100% Renewable Resources based Supply System in Pakistan

Demand Scenario	Supply Case	Transmission Lines Requirements (000 km)				Transmission Lines Requirements (million kV-km)	Sub-Stations Capacity (000 MVA)
		220 kV	500 kV	765 kV	1000 kV		
OG_Demand _Scenario	LW_LPC_Supply_Case	2.2	4.1	6.3	18.1	30.7	173.4
	LW_HPC_Supply_Case	0.5	4.3	7.8	18.7	31.3	163.4
	HW_LPC_Supply_Case	0.6	3.3	4.8	24.3	32.9	199.7
	HW_HPC_Supply_Case	1.2	4.2	6.6	14.8	26.7	175.7
HG_Demand _Scenario	LW_LPC_Supply_Case	1.5	4.9	2.5	17.8	26.6	214.8
	LW_HPC_Supply_Case	0.0	2.4	7.3	24.7	34.4	198.8
	HW_LPC_Supply_Case	0.7	4.5	0.3	31.8	37.3	243.5
	HW_HPC_Supply_Case	0.0	2.5	7.6	36.5	46.6	225.5

11.5 Supply Cases Techno-Economic Comparison

11.5.1 Cost Basis

Renewable energy technologies are in an early phase of penetration into the energy market, and their future cost assessment is debatable. A few well-known organizations including IEA, IRENA etc., regularly forecast their costs in the long-term future. Recently, the Deutsche Institut für Wirtshaft (DIW) evaluated the forecasted values of different organizations, and assessed the learning impacts on the cost by 2050 (Figure 11. 3) (DIW, 2013, p. 77). For this research, the same values were used in the assessment of the total discounted system cost (TDSC). Additionally, the analysis required fixed and variable operation costs of the technologies (TABLE 11. III). For fixed costs, the source is the same, while the variable cost values were taken from the IRENA (2013, p. 69).

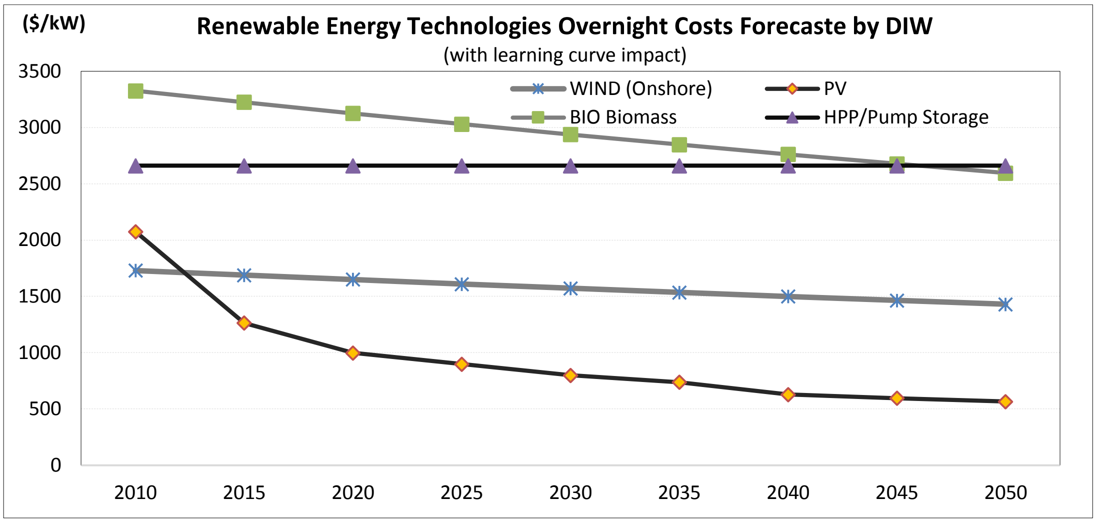


Figure 11. 3: DIW renewable technologies overnight cost forecasts (DIW, 2013, p. 77)

TABLE 11. III: Variable and fixed operational cost values of renewable technologies

Costs	Wind	PV	Hydro*	PHES	Biomass	Reference
Fixed Costs (US $/kW)	26.25	18.75	10.5	15	75	(DIW, 2013, p. 78)
Variable Costs (US cents/kWh)	0.0174	0.021	0.006	0.006	0.02	(IRENA, 2013, p. 69)

11.5.2 Development Pathway in MESSAGE

For modelling of the system in MESSAGE, a same development pathway was assumed for each supply case. In this pathway, a gradual development approach of the renewable resources was used (Figure 11. 4). For controlling the share of the resources, a dummy source of power generation was considered. The dummy source's future installations were limited through applying a high investment cost constraint. The source not only controls for the development of renewable resources installation, but also represents the supply shortage[124] in the early periods. Furthermore, the existing renewable (i.e., mainly hydro) and the non-renewable installed capacities were considered distinctly in the model. The renewable capacity was supposed to remain in the system by 2050, while the model retired the non-renewable capacity after completing the life.

In the model, the operational cost of the existing capacity, including the dummy, were assumed to be zero. The purpose of which was to determine the discounted cost specifically of the proposed supply system of each case. This made the modelling of the system convenient, as the main objective of the task was a comparison of the cases.

11.5.3 System Discounted Costs

The discounted cost of each supply case at LPC and HPC have been determined by using the MESSAGE framework, as mentioned earlier. The framework uses a low temporal resolution, but the results of the hourly simulation overcame the issue. From the hourly simulation, the annual effective capacity factor of each supply case was found. Furthermore, the simulation findings also helped to calculate the weighted average values of MESSAGE input parameters. It is important to mention that the cost included both, the investment and operation costs of the supply cases across the modelling horizon (i.e., 2012-2050).

In TABLE 11. IV, the weighted average parameters used in the model are given, while the calculations done for them are presented as Appendix-J. In the model, a 3.0% discount rate was used to assess the discounted cost of each case (Figure 11. 5).

[124] Represent load-shedding of the system

A comparison of the cases shows that an increase in the wind capacity instead of PV is more cost efficient option in the HG_Demand_Scenario than OG_Demand_Scenario. This also confirms the early discussion of excess generation in the HW_Supply_Case and OG_Demand_Scenario (i.e., the high wind capacity is inefficient in the scenario). Consequently, the system's overall cost is significantly high, particularly at the LPC of the HW_Supply_Case than LW_Supply_Case of the scenario. Finally, in OG_Demand_Scenario, the LW_Supply_Case (i.e., at the LPC) is the most economical one, while in the HG_Demand_Scenario; the economical supply combination is of the HW_Supply_Case (i.e., at the LPC).

A comparison of the two supply cases revealed that a high increase of the PV capacity relative to the wind capacity reduced the overall learning curve impact i.e. In OG_Demand_Scenario, the system cost is 157 billion US$ at the LPC. The cost reached to 187 billion US$ at the HPC (i.e., with an increase of PV), while the system cost in presence of high wind capacity is 182 billion US$ in the scenario. The same phenomenon can be observed for the HG_Demand_Scenario.

Similarly, the higher cost values at the HPC more than the LPC are understandable. At the LPC, the seasonal storage capacity requirements are more than HPC. However, the high difference of the PV capacities relative to the difference of the seasonal storage system capacity at the operational point made the LPC the more economical option.

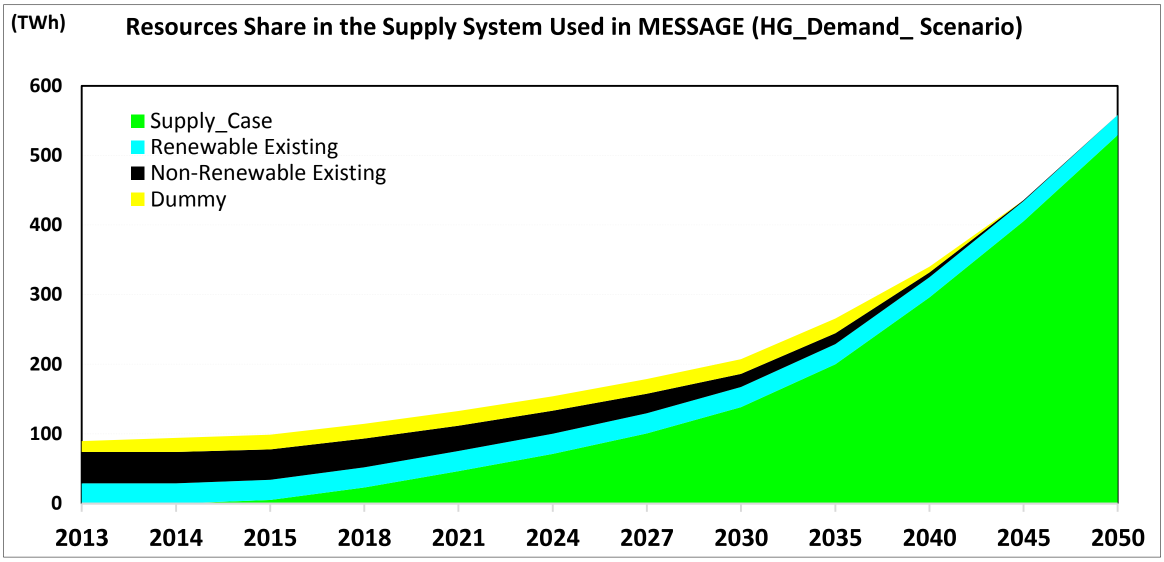


Figure 11. 4: Share of a renewable supply case and other resources in the demand fulfillment of the High_Demand_Scenario (MESSAGE model assumptions)

TABLE 11. IV: Weighted average values of the parameters used in MESSAGE

Demand Scenario	Supply Case	Variable Cost (US$ /kWYr)	Fixed O&M Cost (US$/kW/Yr)	Invest Cost ($/kW)	Capacity Factor	Life (Years)	Cons. Period (Years)
OG_Demand_Scenario	LW_LW_Supply	1.15	22.97	2341.05	0.26	33.40	3.22
	LW_HW_Supply	1.31	18.03	1951.19	0.17	28.79	2.80
	HW_LW_Supply	1.12	25.13	2456.61	0.26	34.77	3.23
	HW_HW_Supply	1.24	19.90	2095.31	0.19	30.66	2.89
HG_Demand_Scenario	LW_LW_Supply	1.25	21.79	2203.57	0.26	32.06	3.11
	LW_HW_Supply	1.35	17.81	1893.06	0.17	28.25	2.76
	HW_LW_Supply	1.22	22.40	2222.36	0.25	32.18	3.04
	HW_HW_Supply	1.36	17.90	1885.84	0.16	28.08	2.69

11.5.4 System Energy/Power Generation Cost

Like the discounted total cost, the per unit cost also depends upon the development pattern of the supply resources, use of excess generation (i.e., effective capacity factor), learning curve impact of the technologies, and interest rate. Considering the previous section information, the generation cost (i.e., the cost per unit of generation) was assessed to be in the range of 04-06 US$ cents/kWh across the period (i.e., 2012 to 2050). This also included the capacity replacement cost. However, the cost reasonably raised when incorporated the impact of I) thermal losses, and II) excess generations. To give an idea about this rise in the cost, Figure 11. 6 presents per unit cost, I) by generation, II) considering thermal losses and no use of excess generation, III) considering thermal losses and utilizing 50% of the excess generation, IV) considering thermal losses and utilizing 100% of the excess generations, in the LW_Supply_Case and OG_Demand_Scenario at the LPC. In the figure, difference in various operational conditions can be observed. This difference in the costs is more obvious at the HPC of all the supply cases.

11.6 Chapter Summary

The simulation of the demand-supply balance showed that the supply system required a seasonal storage support to meet the demand. The resources capacity and energy requirements, both increased with an increase in the demand. The results also showed that the increase of the wind resources is more effective with an increase in the demand to operate the system efficiently. Similarly, the transmission system requirements also increased with the demand. Furthermore, the transmission losses increased when the system is actually supposed to be operating more efficiently.

Additionally, the MESSAGE framework has been used to estimate the discounted cost of the system by 2012. This cost is estimated to be 162 to 185 billion US$ in the OG_Demand_Scenario and 210 to 240 billion US$ in the HG_Demand_Scenario in different supply cases.

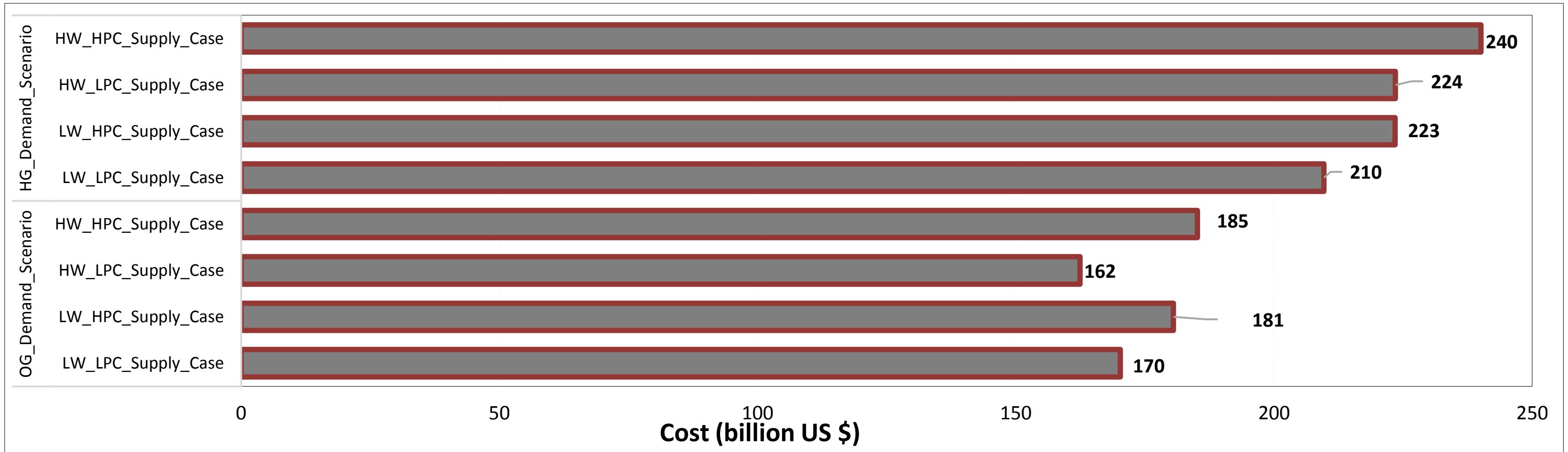


Figure 11. 5: Pakistan's 100% renewable resources based electric power system total discounted cost by 2050 (findings)

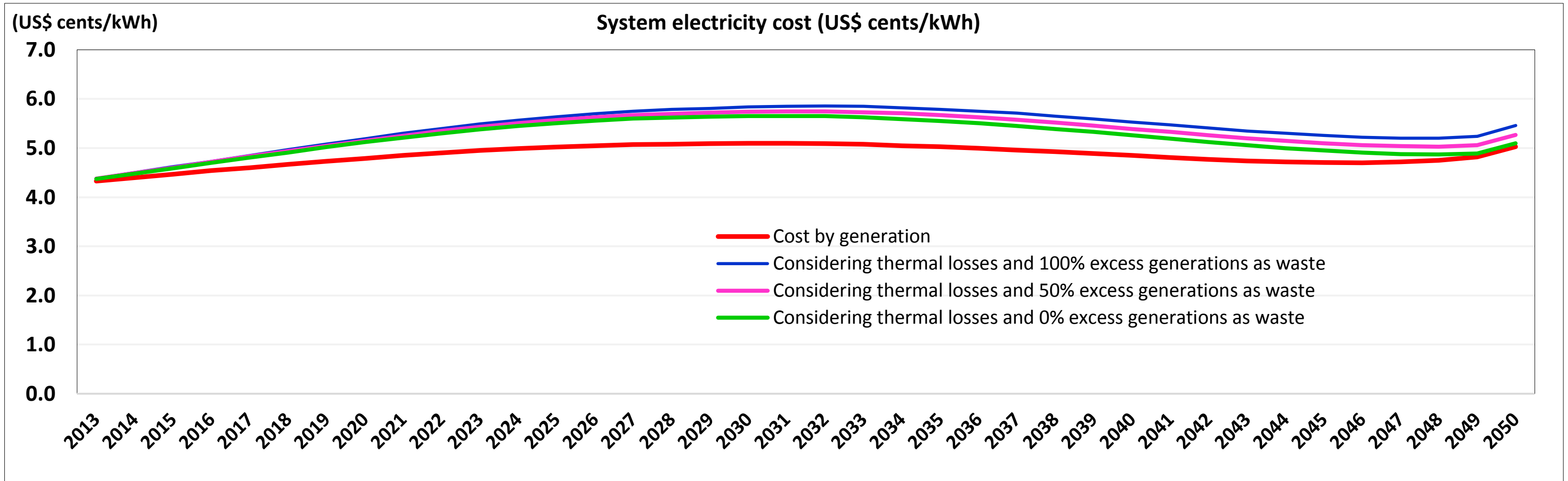


Figure 11. 6: Proposed 100% renewable electric supply system per unit cost

Chapter 12 Research Summary

Renewable resources are recognized among the options toward a sustainable energy system[125]. Experts have perceived a significant share of the resources to handle the Climate Change issue and to slow down the global warming process (IPCC, 2014, pp. 217,556-558). Overall, experts were convinced of this even as long as a decade ago, regarding the technical feasibility of a renewable resources based energy supply system (Pacala & Socolow, 2004, pp. 968-972). The concerns are, therefore, now more about the resources adequacy and an efficient as well as economical operation of the system.

To achieve the desired renewable contributions in the future, long-term policies should encompass reasonable targets of the resources. At the same time, the target to be managed for implementation. As a part of the efforts, the research work was carried out for Pakistan's power system. The work evaluated a proposed 100% renewable resources based electric power system in the country. This chapter summarizes the research limitations and findings in a descriptive way. It also contains some recommendations for the development of the system, with a few research proposals for further improvement.

12.1 Research Limitations

This research was carried out as a part of a PhD work, therefore the work was limited both by time and financial resources. In the following, the major limitations are briefly described.

- For this analysis, substantial data and information of the renewable resources were required. In some cases, particularly wind and solar resources data, there was limited information within the country. For this research, therefore, alternative options were used to fill the data gaps. In the near future, the resultant database of the World Bank program for the country (ESMAP, [n.d], p. [online]) can be a good source of information for the analysis.
- In this research, the PEPCO's demand pattern has been applied to all the regions. However, there is a high probability of a different pattern in each region, due to the climate diversity and difference of the social as well economic development. Currently, there is no published information regarding the regional patterns. Applying the patterns will have obvious impacts on the regional utilization and inter-regional power flow. However, the overall demand pattern will remain the same, and therefore, only a limited impact can be expected on the resources contribution.

[125] According to Lund (2010), biomass does not lie in the category of the sustainable option. Therefore, the option is an exception while generalizing the sustainability concept for renewable resources.

The electricity demand pattern is a sum of the regions total demand. This means that some regions may export a surplus of energy, while others have to import energy in order to meet demand. For example, a region may spare and/or export generated power in an hour, which was supposed to be used by it. In this context, another region may import from the early one, in the hour to meet its demand.

- The demand profile in Pakistan will most probably change in the future with more development, particularly in the industrial sector. The main advantage of which will be relatively a flat demand profile across a year. However, this profile could modify the findings, particularly the requirements of seasonal storage during the winter and spring.
- The development of a renewable supply system will have a large impact on different systems, including; ecological, environmental, social, etc. In this research, no such impacts were analyzed due to resource and time limitations.
- For analysis, Pakistan's power system was considered in a standalone mode. However in the future, the grid system will integrate with other regional systems (i.e., countries). For example the CASA[126] 1000 kV transmission line between Central Asia (Kyrgyz Republic and Tajikistan) and South Asia (Afghanistan, Pakistan) is under development and will integrate Pakistan's power system to the other regional systems (NTDC, 2013b, p. 1). Considering such development will definitely affect the findings of the research. The operational scenario can therefore, be more attractive in balancing the residual demand in a case of shortage or to export the extra energy generations.
- Bearing in mind the impacts of Climate Change, the renewable resources availability may change in the long-term future. However, the information regarding the prospective changes and their impacts on the resources availability are limited. It will be, therefore, important to regularly simulate the study with updated information.
- In this research, the transmission system was assumed to support the inter-regional flows without limits on the lines capacity. The approach was used to efficiently utilize the renewable resources through a significant inter-regional power flows. The analysis revealed that the most extensive expansion will be required in order to transmit the hydropower generations. By applying these limits, there will be certain changes in the supply mix of the resources and their utilization.

[126] CASA stand for Central Asia, South Asia

12.2 Findings and Contributions

- The renewable resources of Pakistan are sufficient and can fulfill the electricity demand by 2050. Obviously, in this analysis, the capacity's requirements of the renewable resources changed according to the demand. However, the increase is not in a linear fashion due to the seasonal variations in the demand and resources availability. Although both are maxed out during summer, but the resources availability during the winter and spring time are so limited that the supply system needed a higher capacity during the periods. It means that the role of the seasonal storage systems (i.e. biomass, hydropower) is critical for an efficient operation of the system, particularly when the demand is above 400-450 TWh.
- The system needed PHES system support in order to operate. However, the operation required the intermittent resources generation accordingly, which can result in more losses and annual excess generation. This means that its value can be adjusted according to the combination of the supply resources, particularly during a seasonal storage. In this work, the 4GW-14 GW capacity was assessed under different demand (430 TWh-556 TWh) and supply conditions.
- Pakistan's hydro resources are substantial and the simulation of the river system showed that an average 11-16 BCM water will be available for storage, even after the construction of the proposed two reservoir based HPPs (RHPP). This water can be stored (most probably by diverting at suitable river point(s)) to contribute as a seasonal storage supply system. It can pass through different RORHPP and RHPP to generate this power, but the final generation will depend upon the storage location. For example, a 4-14 TWh energy can be generated only when the water passes through the three RHPP[127] along the Indus River.
- For a seasonal hydro storage, if the reservoir location(s) is such that it needed a pumping support, the option is still a convincing one. Because, during the high flow period, a reasonable quantity of extra power generations were found in the demand-supply balance of almost all the supply cases. These extra generations can be used to serve the pumping loads of the proposed seasonal storage system.
- The simulation results showed that the biomass potential can play a vital role in the 100% renewable based supply system. A reasonable potential of the resources can significantly reduce the total installed capacity requirements. The analysis showed that the system needed a seasonal storage support of 4.4%-18%, in the two demand scenarios and

[127] Diamer Bhasha, Tarbela and Kalabagh

different supply combinations. However, the value will grow faster with a further increase in demand.

- Keeping in mind the technical limitations of biomass based generations, a combination of the hydro and the biomass as a seasonal storage supply system is highly desired, particularly at the demand value above 400-450 TWh.
- The country's wind resources can play an important role in the development of a 100% renewable resources based supply system. The resources can serve nighttime demand and therefore, can minimize the PHES as well as the seasonal storage requirements. In the presence of all of the hydropower potential resources, their integration will not be a big challenge for a reliable operation of the system.
- For an efficient operation of the system, it is important to keep the capacity of the wind resources according to the demand level. In this analysis, considering the total capacity at a demand value of 430 TWh resulted in a substantial excess generation during summer. However, in the case of high demand (556 TWh), the resources were relatively efficient and vital in order to meet the demand.
- For implementation of the system, a substantial infrastructure of the transmission system will be required. The highest power flow (42-50 GW) was assessed between the northern areas and the major load centers (i.e., central and northeastern parts). Similarly, in the south, a major expansion was assessed for the transmission of the Baluchistan wind resources.
- A model for hourly demand-supply balance of Pakistan power system has been developed. The model can find the balance for the system, considering different capacities of the renewable resources. In a next step, it is planned to make the model as a general tool. This will be really helpful in analyzing the system at a high spatial resolution. Furthermore, it can be helpful to model a hydropower generation system, particularly when the generation units layout is a cascading one.

12.3 Recommendations

Pakistan can develop a 100% renewable resources based electricity supply system using indigenous resources with the efforts of planning and implementation. Based on the findings and system's knowledge, a few recommendations are presented below to support and initiate the efforts.

- The research was performed with the above-mentioned data limitations. It is important to incorporate the updated information and regularly execute the kind of analysis to constantly improve the findings. The process can also help to incorporate new scenarios based on the updated data and knowledge of the system.

- The GOP will primarily need a continue planning process to develop the system. The policy should be focused to devise an implementation program, and to incorporate the desires of the stakeholder to a necessary limit. Currently, the feed-in tariff and other incentives in the country are good for the development of the system. However in the future, the government will need to intensify the efforts and support the program at all levels of the planning and development process.

- In Pakistan, a few institutes and departments are working in the domain of the power system's policy formulation. Most of them work independently and coordinate on a limited scale. In addition, the academia contribution is negligible and have almost no impact on the planning process. Using the existing resources, the GOP can develop a centralized policy entity to interact with the involved institutes. The entity can coordinate and incorporate the contributions of all participating institutes and departments in the transition process.

- Historically, the electric power system of Pakistan is highly static in regards to the demand side of management. The system hardly employed new technologies for the improvement of the system operation and management of the demand. In the market, sophisticated metering and load control systems are available to help in the demand management. For example, prevention of the auxiliary services during peak hours of the demand, etc.

- The GOP and International community support the initiatives of renewable development in the country from time to time. However, due to the presence of several departments and entities, the efforts are not centralized. For example, PMD and the USAID worked out the wind resources potential of the country (PMD, n.d(a), p. [online]). Now recently, AEDB initiated a project of the same type with the World Bank (ESMAP, [n.d], p. [online]). At the time, the role of PMD is unknown, but AEDB can probably deliver more effectively, if coordinates the efforts with PMD.

- According to the World Bank (2005, p. 11), the flows in IRS will rise 30-40% in the next fifty years, and then will decrease by the same scale below the current level. This is a challenging situation for the country and needed adaptation efforts. Fortunately, the development of reservoirs can help the country in both scenarios. In the first scenario, the reservoirs can help in limiting the flood intensity. In the second scenario, they will store the water to meet the demand, during the period of low water availability. Such development will directly support a power supply system based on the renewable resources in Pakistan.

- In Pakistan, power generation facilities using the intermittent resources (i.e. wind and solar) are connected to the grid system. The generations are being handled by the system without a major problem due to the presence of enough hydropower generation and/or supply shortages. However, a high share of the resources will need the development of PHES system for an efficient and reliable operation.

12.4 Further Research

The research is interdisciplinary and the work, therefore, incorporated diverse details. However, the research provided a basic structure and a model for the developments of the renewable resources in the country. In the future, thorough investigation of the relevant systems can further improve the findings and can facilitate the implementations. Moreover, the ongoing efforts of the resources assessment can provide more information for the analysis, which will minimize the above-mentioned limitations. In the future, the following research efforts among others can contribute to the refinement of the findings[128].

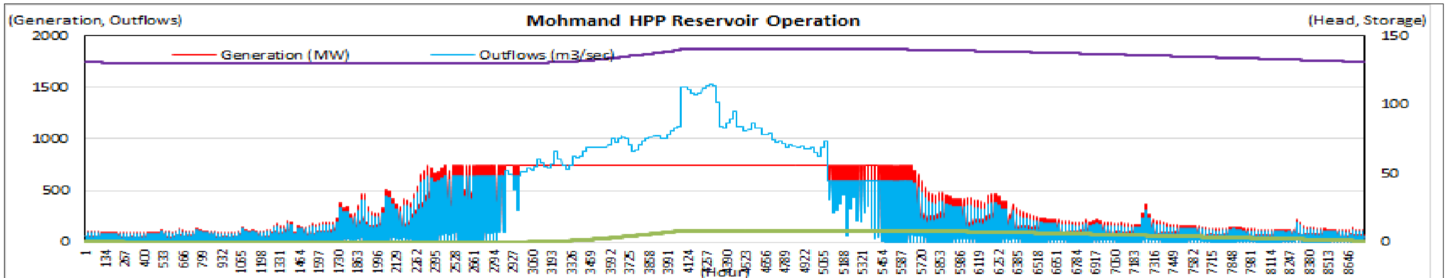
- In this research, only the power system was considered within the strict demand pattern. Consequently, the analysis showed substantial excess generation. These excess generation can be reduced, if the demand consist of fix and flexible components. In real situation, this can be achieved by considering a battery-charging load, gas (hydrogen) production using electricity, etc. In the case, the system performance and economics can be improved. It is, therefore, recommended to add such an operational scenario to the analysis.
- The research considered only the demand-supply scenario in 2050. However, the emerging approach (hybrid modelling) is to develop an expansion plan, considering a gradual increase of the renewable scenario. For this type of modelling and analysis, the model of this research can be used in combination of Pak-IEM. For which, some modifications in Pak-IEM and incorporation of economic optimization in the research model will be required.
- It is important to assess the development impact of a renewable resources based electric supply system. The most obvious impacts will be on the ecological and land-use in different parts of the country. Furthermore, the social benefits of the development e.g., job creation, electrification etc., and supply security as well as the GHG emission reduction can

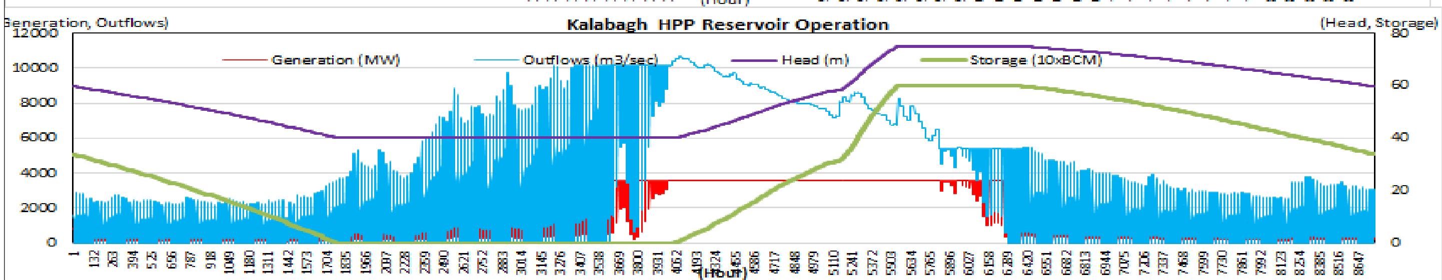
[128] The author can be contacted for coordination

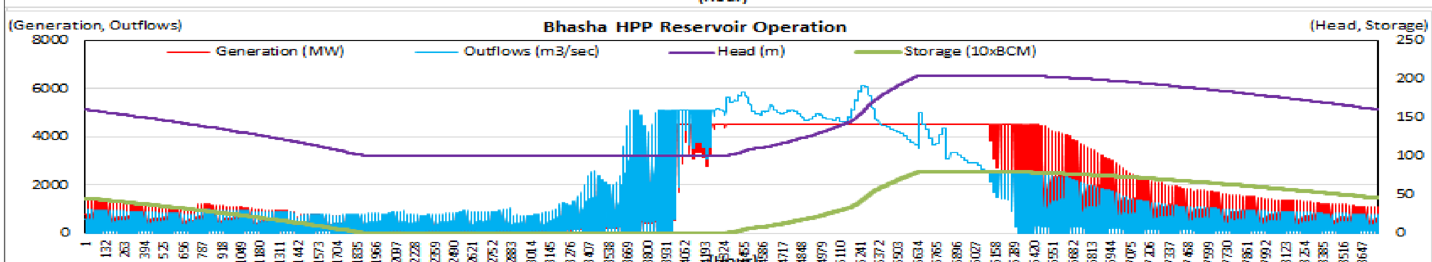
also be included in the analysis. The research will help to weigh the pros and cons of the system development.

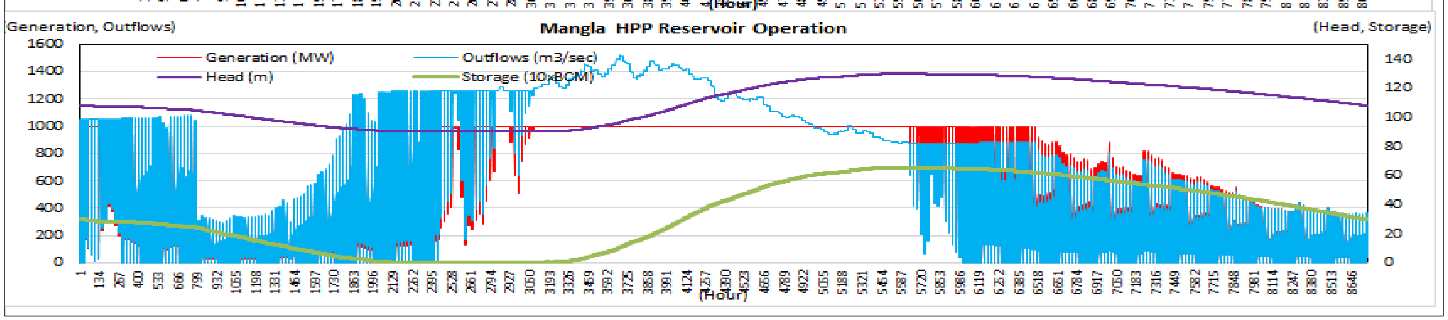
- Developing a financial plan and devising an implementation pathway can be useful for decision-making process. Additionally, development of a business model can be important for a smooth transition of the system and implementation of the renewable resources.
- Assessment of the regional load patterns in Pakistan, particularly of the residential and commercial sectors are important for the refinement of the work. For the purpose, the information can be collected from the DISCOs in the country. OR, a generic approach can be used, to link different variables (i.e., weather pattern, income, use pattern of the electric appliance, etc.,) with the consumption to assess the regional demand patterns.
- What is the potential of the PHES system in Pakistan? Although, the task has been initiated in this research, it is only superficial and meant to support the assumptions. Therefore, a thorough study on the topic can help in the minimization of the uncertainties. For the research, a general approach is to use GIS, online maps etc., with specified guidelines. The research work should be focused on the whole country, particularly to investigate the southern and central parts. In the regions, the resources role is highly desired for the development of the system.
- In this research work, the demand-supply balancing criterion in the model was the fulfillment of the demand. In the model, the resources economics as well as the transmission limitations can also be incorporated in the decision making process.
- Working out the potential of distributed generation in the remote areas of Pakistan, particularly the areas which are currently not electrified. The research work can be carried out to determine the basic energy needs and the available resources in specific areas. The work can incorporate the social benefits of the electrification, which can boost the renewable development in the country.

Appendix-A: Reservoir base HPPs Operation





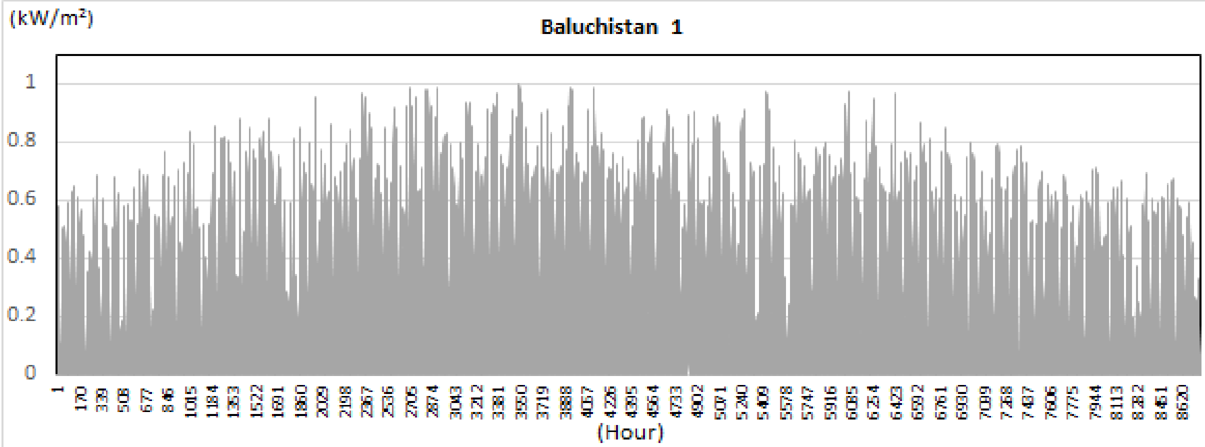


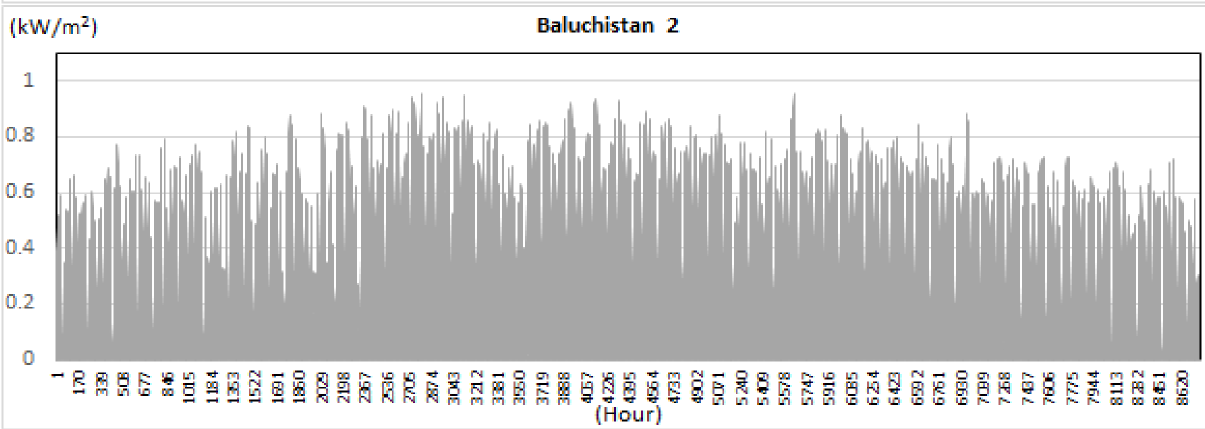


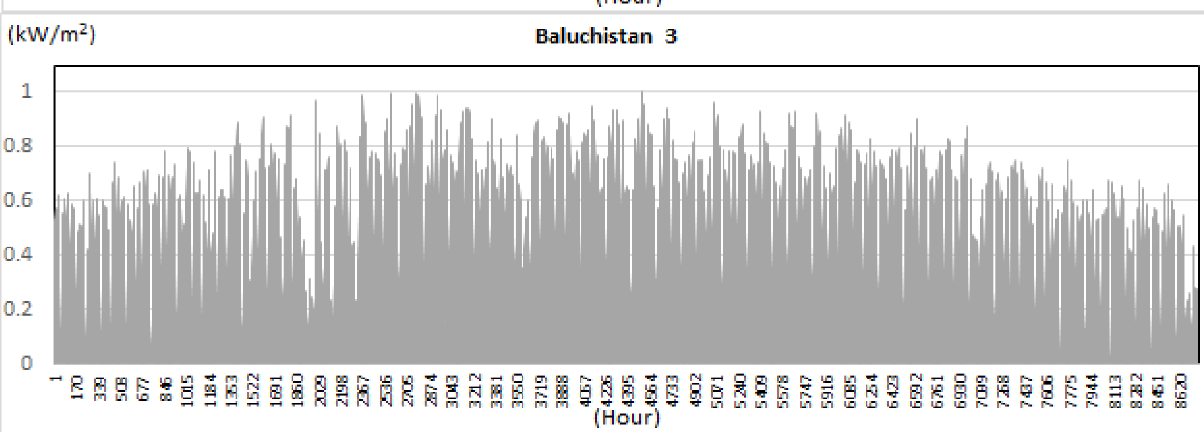
Appendix-B: Assessment of Pump Storage Potential

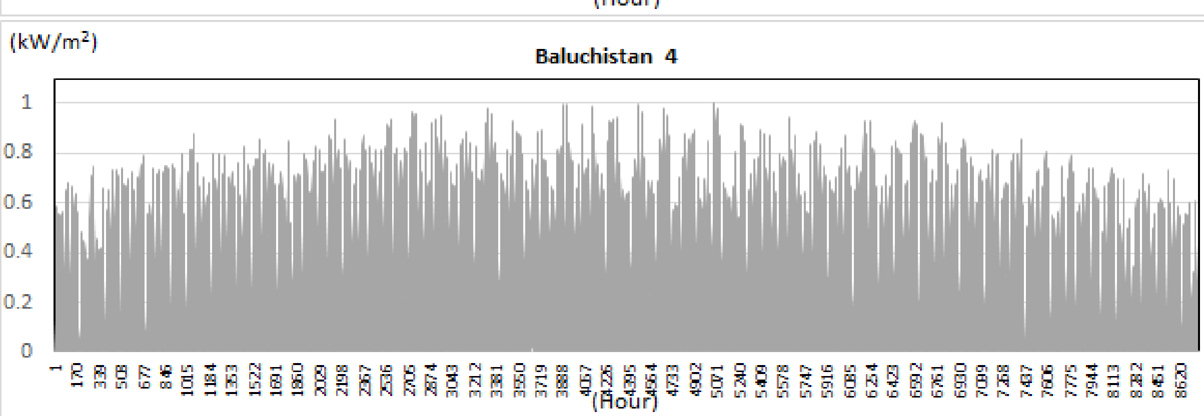
S. No	Site Name	Region	Location 1 altitude (m)	Location 2 altitude (m)	Head (m)	Distance (km)	Area (km2)	Depth (m)		Volume (m3)		18 Hours Flow (m3/Sec)		Potential (MW)	
								Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
1	Sheosare Lake	GB	4144.6	4005.8	138.8	2.2	1.4	10	20	14200000	28400000	493	986	670.9	1341.8
2	Borith Lake	GB	2657.0	2437.0	220.0	1.0	0.2	10	25	1500000	3750000	52	130	112.3	280.7
3	Naltar Lake	GB	3456.8	3258.8	198.0	1.2	0.2	10	25	2300000	5750000	80	200	155.0	387.4
4	Rush Lake	GB	4617.7	3244.0	1373.7	3.5	0.0	10	25	400000	1000000	14	35	187.0	467.4
5	Satpara Lake	GB	2687.0	2192.6	494.4	3.0	2.4	10	25	24100000	60250000	837	2092	4054.0	10135.1
6	Shandoor	GB	3685.1	3610.8	74.3	4.2	1.6	10	25	15700000	39250000	545	1363	397.1	992.7
7	Kachura	GB	2295.8	2178.3	117.4	0.7	0.3	10	25	2600000	6500000	90	226	103.9	259.7
	Total													**5680.1**	**13864.8**
8	Hanna Lake	Baluchistan	1904.4	1887.6	16.8	1.1	0.5	10	25	4600000	11500000	160	399	26.3	65.8
9	Hub Lake	Baluchistan	524.5	529.0	4.5	0.5	0.5	10	25	4500000	11250000	156	391	6.9	17.2
10	Zangi Lawar	Baluchistan	926.0	913.2	12.8	6.6	9.7	10	25	96600000	241500000	3354	8385	421.7	1054.2
	Total													**454.9**	**1137.2**
11	Sari Paya	KP 1	3001.0	2093.0	908.0	1.4	0.8	10	25	7800000	19500000	271	677	2410.0	6025.0
12	Aansu Lake	KP 1	4139.0	3663.7	475.3	1.9	0.0	10	25	100000	250000	3	9	16.2	40.4
13	Dudipatsar Lake	KP 1	3907.2	3809.0	98.2	1.3	0.3	10	25	2900000	7250000	101	252	96.9	242.3
14	Kundol Lake	KP 1	4082.0	3041.8	1040.2	1.7	0.5	10	25	4500000	11250000	156	391	1592.8	3982.0
15	Saiful Muluk Lake	KP 1	3217.3	2884.0	333.3	1.9	0.5	10	25	4500000	11250000	156	391	510.3	1275.8
16	Tanda Lake	KP 2	302.8	299.2	3.5	0.2	0.2	10	25	1500000	3750000	52	130	1.8	4.5
17	Chitta Katha Lake	KP 1	4066.2	3578.3	487.8	1.7	0.7	10	25	7200000	18000000	250	625	1195.2	2988.0
	Total													**5823.2**	**14558.0**
18	Saral Lake	AJK	4038.3	3604.6	433.7	3.2	0.2	10	25	2300000	5750000	80	200	339.4	848.5
19	Ratti Gali Lake	AJK	3690.5	3724.0	33.5	2.6	0.9	10	25	9100000	22750000	316	790	103.6	259.0
20	Zalzal Lake	AJK	1228.1	1193.0	35.1	1.0	0.5	10	25	4500000	11250000	156	391	53.8	134.4
21	Gumma Lake	AJK	319.8	311.8	8.0	0.3	0.1	10	25	500000	1250000	17	43	1.4	3.4
22	Jabba Kas Lake	AJK	281.2	275.5	5.8	0.5	0.7	10	25	7200000	18000000	250	625	14.1	35.3
	Total													**512.2**	**1280.6**
23	Wana	FATA	994.2	945.8	48.4	2.2	2.7	10	25	26800000	67000000	931	2326	441.2	1103.1
24	Baran Lake	FATA	437.0	429.8	7.2	2.9	5.9	10	25	59300000	148250000	2059	5148	145.1	362.8
	Total													**586.4**	**1465.9**
	Grand Total													**13056.8**	**32306.5**

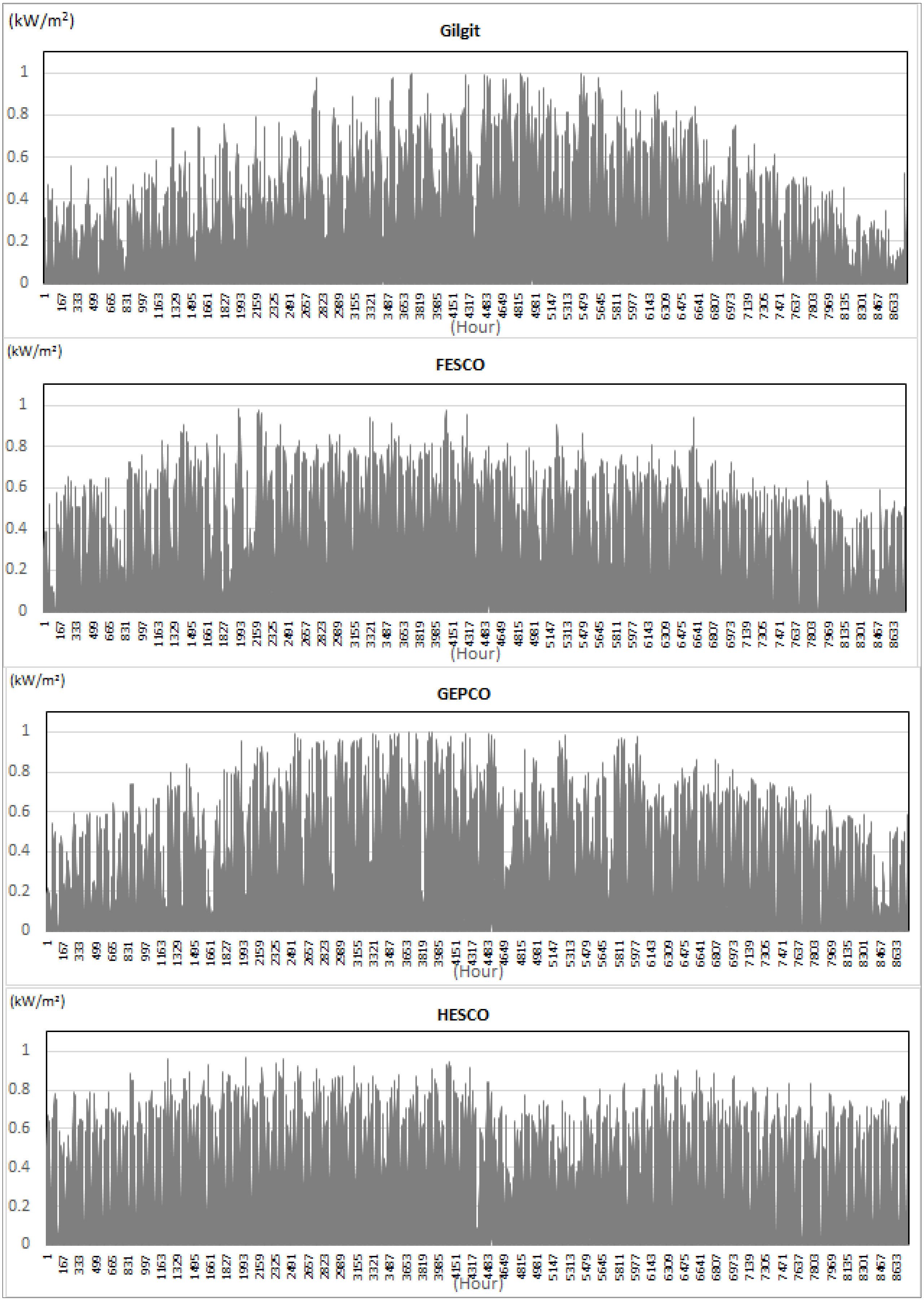
Appendix-C: Regional Hourly Solar Insolation (kW/m^2)

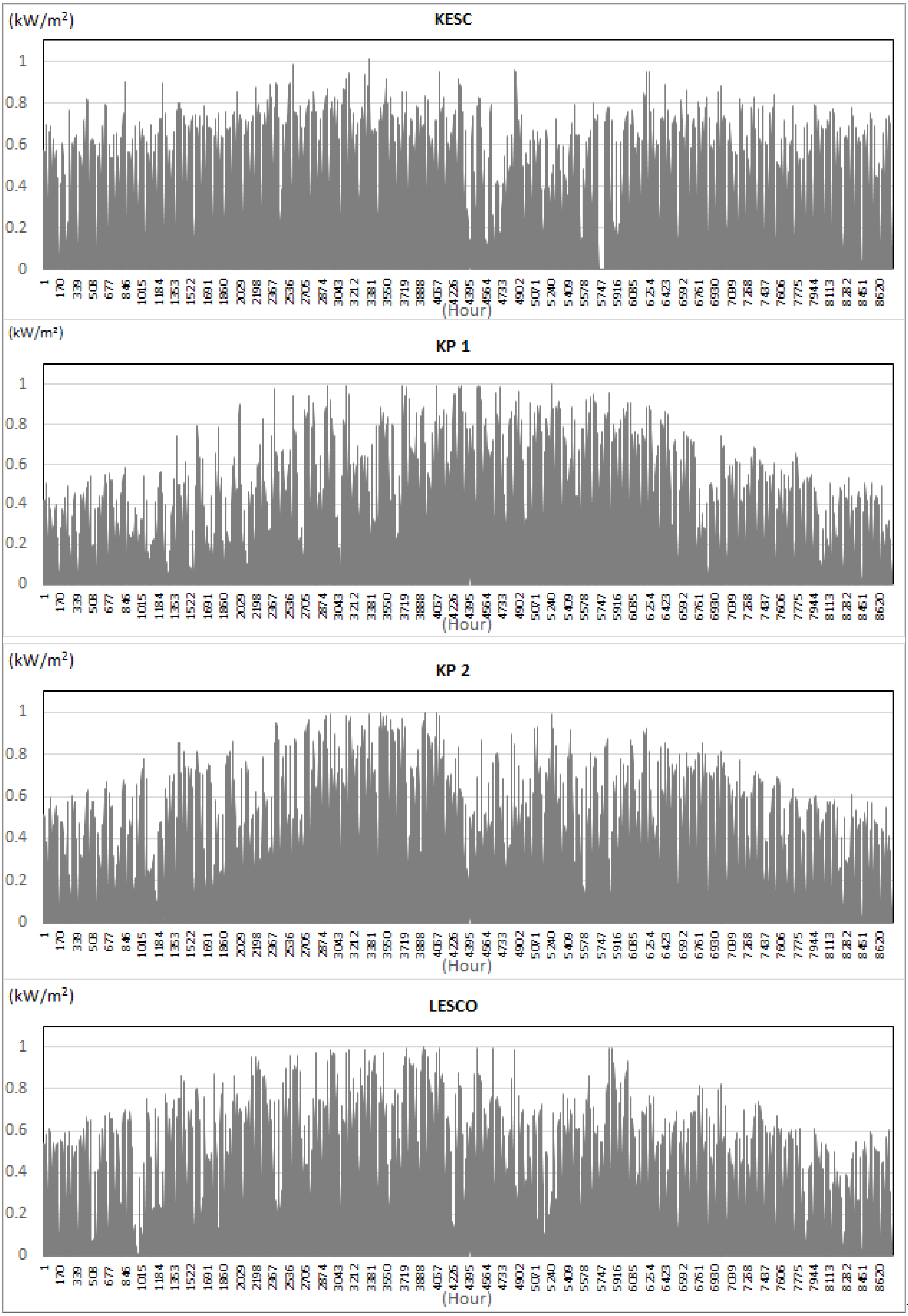


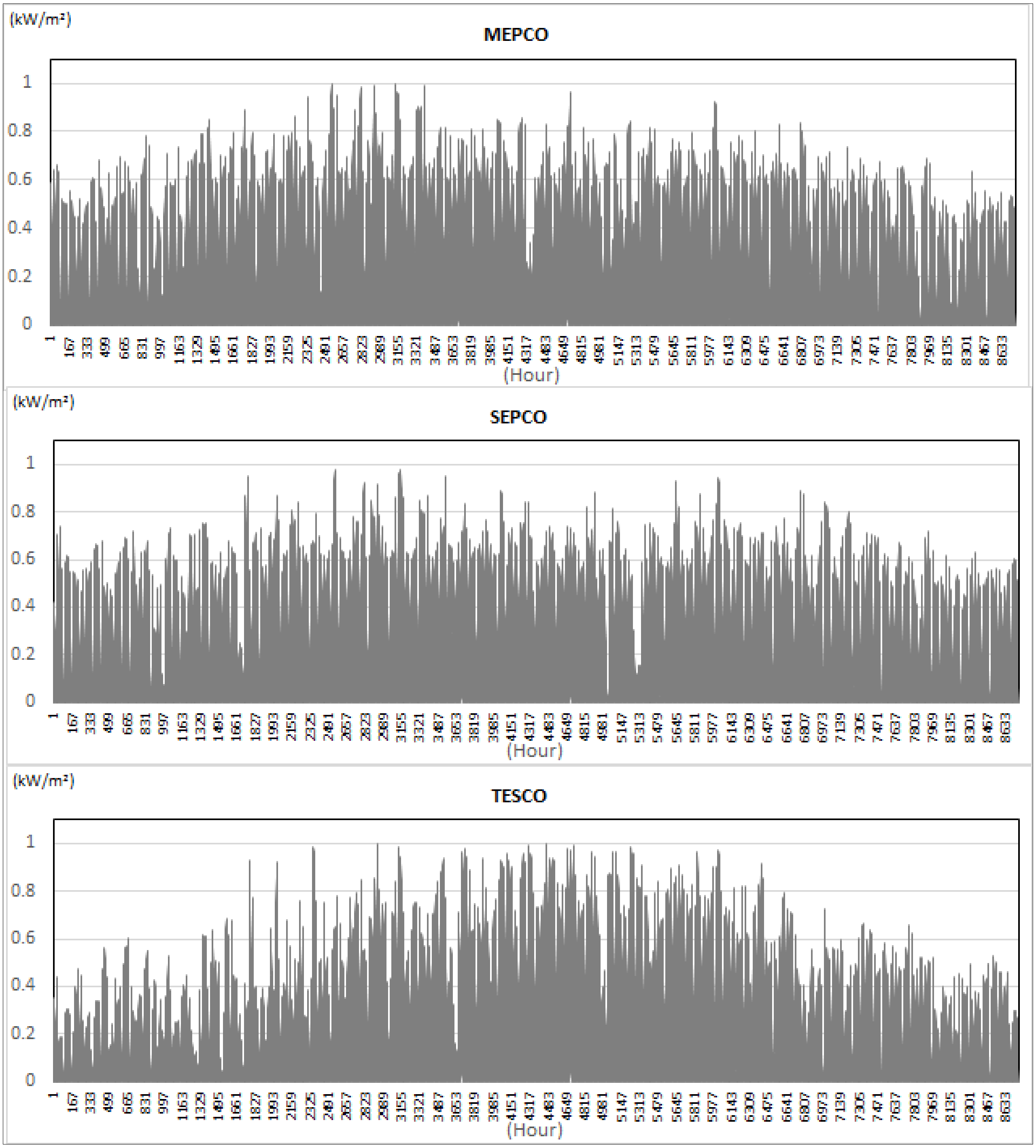







(kW/m²)
Gilgit
(Hour)
(kW/m²)
FESCO
(Hour)
(kW/m²)
GEPCO
(Hour)
(kW/m²)
HESCO
(Hour)


(kW/m2)
KESC
1
0.8
0.6
0.4
0.2
0
1 170 339 508 677 846 1015 1184 1353 1522 1691 1860 2029 2198 2367 2536 2705 2874 3043 3212 3381 3550 3719 3888 4057 4226 4395 4564 4733 4902 5071 5240 5409 5578 5747 5916 6085 6254 6423 6592 6761 6930 7099 7268 7437 7606 7775 7944 8113 8282 8451 8620
(Hour)
(kW/m²)
KP 1
1
0.8
0.6
0.4
0.2
0
1 170 339 508 677 846 1015 1184 1353 1522 1691 1860 2029 2198 2367 2536 2705 2874 3043 3212 3381 3550 3719 3888 4057 4226 4395 4564 4733 4902 5071 5240 5409 5578 5747 5916 6085 6254 6423 6592 6761 6930 7099 7268 7437 7606 7775 7944 8113 8282 8451 8620
(Hour)
(kW/m2)
KP 2
1
0.8
0.6
0.4
0.2
0
1 170 339 508 677 846 1015 1184 1353 1522 1691 1860 2029 2198 2367 2536 2705 2874 3043 3212 3381 3550 3719 3888 4057 4226 4395 4564 4733 4902 5071 5240 5409 5578 5747 5916 6085 6254 6423 6592 6761 6930 7099 7268 7437 7606 7775 7944 8113 8282 8451 8620
(Hour)
(kW/m2)
LESCO
1
0.8
0.6
0.4
0.2
0
1 170 339 508 677 846 1015 1184 1353 1522 1691 1860 2029 2198 2367 2536 2705 2874 3043 3212 3381 3550 3719 3888 4057 4226 4395 4564 4733 4902 5071 5240 5409 5578 5747 5916 6085 6254 6423 6592 6761 6930 7099 7268 7437 7606 7775 7944 8113 8282 8451 8620
(Hour)
V


(kW/m²)
MEPCO
(Hour)
(kW/m²)
SEPCO
(Hour)
(kW/m²)
TESCO
(Hour)

Appendix-D: Demand Forecasting Details

DEMAND DRIVERS

YEAR	OG_Demand_Scenario (4.2% Avg. Annual Growth Rate)					HG_Demand_Scenario (5.0% Avg. Annual Growth Rate)				
	Agriculture	Industry	Commercial	Total	Population (million)	Agriculture	Industry	Commercial	Total	Population (million)
2012	---	---	---	---	183	---	---	---	---	183
2013	---	---	---	---	185	4.45%	4.45%	4.37%	4.40%	185
2014	4.45%	4.45%	4.37%	4.40%	188	3.62%	3.62%	4.95%	4.39%	188
2015	3.62%	3.62%	4.95%	4.39%	192	3.50%	3.80%	5.30%	3.67%	192
2018	3.50%	3.80%	4.00%	3.67%	202	2.88%	3.90%	5.40%	4.80%	202
2021	3.60%	3.90%	4.50%	4.04%	211	3.00%	4.00%	5.55%	4.60%	211
2024	3.50%	4.00%	4.40%	4.19%	221	3.43%	4.15%	5.87%	4.76%	221
2027	3.25%	4.15%	4.30%	4.14%	230	3.20%	5.50%	5.37%	5.10%	230
2030	3.00%	4.20%	4.35%	4.06%	240	3.30%	5.60%	5.30%	5.02%	240
2033	2.60%	4.10%	4.50%	4.06%	250	3.30%	5.07%	5.60%	5.03%	250
2036	2.60%	4.06%	4.68%	4.06%	260	3.30%	5.07%	5.60%	5.14%	260
2039	2.60%	4.06%	4.68%	4.18%	270	3.30%	5.07%	5.60%	5.16%	270
2042	2.60%	4.06%	4.68%	4.20%	280	3.30%	5.07%	5.60%	5.18%	280
2045	2.60%	4.06%	4.68%	4.21%	291	3.30%	5.07%	5.60%	5.19%	291
2048	2.60%	4.06%	4.68%	4.23%	302	3.30%	5.07%	5.60%	5.21%	302
2050	2.60%	4.06%	4.68%	4.25%	309	3.32%	4.40%	5.39%	5.22%	309

Projected Intensities and Life Style Improvements

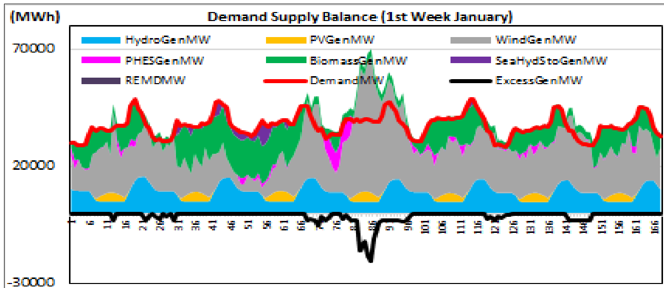
Year	Electricity Consumption Intensities (kWh/PRs.) (HDIP, 2013, p. 84), (Ministry of Finance, 2014, p. [Table 12.1]), (Planning Commission, 2010a, pp. 41-43).			Residential (kWh/Capita)	
	Agriculture	Industry	Commercial	OG_Demand_Scenario	HG_Demand_Scenario
2012	0.00418	0.01096	0.0019712	272	272
2015	0.00436	0.01087	0.0019541	303	306
2018	0.00455	0.01078	0.0019371	337	345
2021	0.00475	0.01068	0.0019202	367	384
2024	0.00496	0.01059	0.0019035	401	427
2027	0.00517	0.01050	0.0018870	437	476
2030	0.00540	0.01041	0.0018706	478	531
2033	0.00564	0.01041	0.0018706	510	580
2036	0.00588	0.01041	0.0018706	545	634
2039	0.00614	0.01041	0.0018706	583	694
2042	0.00641	0.01041	0.0018706	626	764
2045	0.00668	0.01041	0.0018706	669	837
2048	0.00698	0.01041	0.0018706	718	920
2050	0.00728	0.01041	0.0018706	769	1003

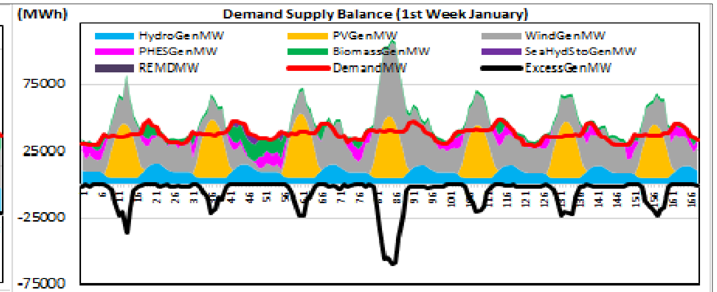
Forecasted Demand (TWh)

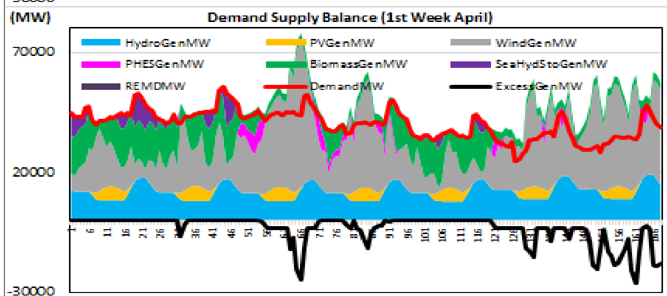
Year	OG_Demand_Scenario						HG_Demand_Scenario					
	Residential	Agriculture	Industrial	Commercial	Transport	Total	Residential	Agriculture	Industrial	Commercial	Transport	Total
2012	50	9	22	11	0	91	50	9	22	11	0	91
2015	58	10	24	12	0	104	59	10	24	12	0	105
2018	68	11	27	14	0	120	70	11	27	14	0	122
2021	78	13	30	16	0	136	81	13	30	17	0	140
2024	88	15	33	18	0	154	94	14	33	20	0	162
2027	101	17	37	20	0	175	110	17	37	23	0	187
2030	115	20	42	22	0	199	127	19	43	27	0	216
2033	127	22	47	26	0	222	145	22	51	31	0	249
2036	142	25	53	29	0	249	165	25	59	37	0	286
2039	157	28	60	34	0	279	187	29	69	43	0	328
2042	175	32	67	39	0	313	214	34	80	51	0	378
2045	195	36	76	44	0	351	243	39	92	60	0	434
2048	217	40	86	51	0	393	278	44	107	70	0	500
2050	238	44	93	56	0	430	310	50	118	79	0	556

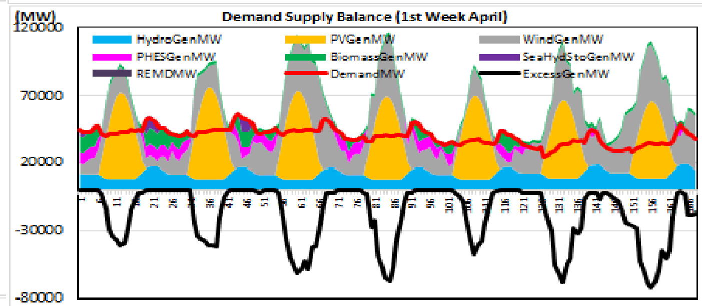
Appendix-E: Weekly Demand-Supply Balances

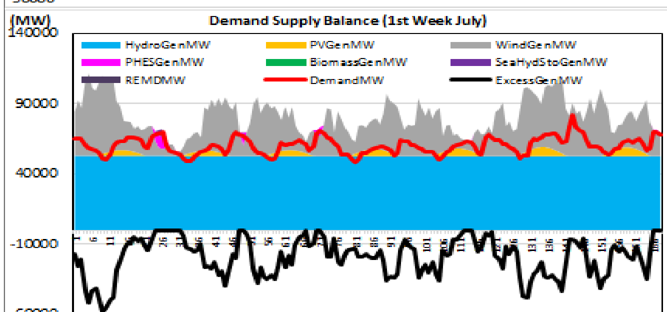
HW_Supply_Case and OG_Demand_Scenario

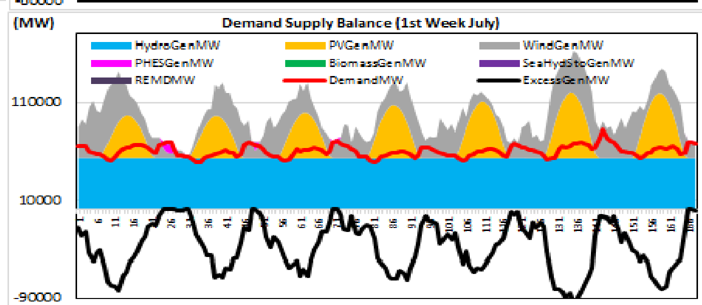


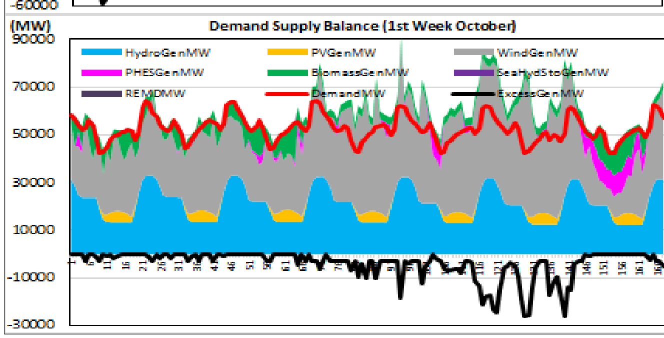


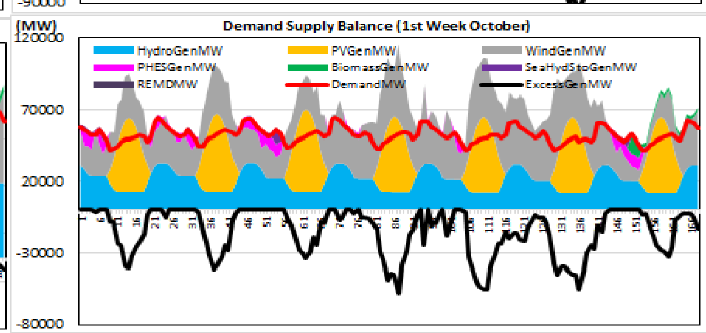




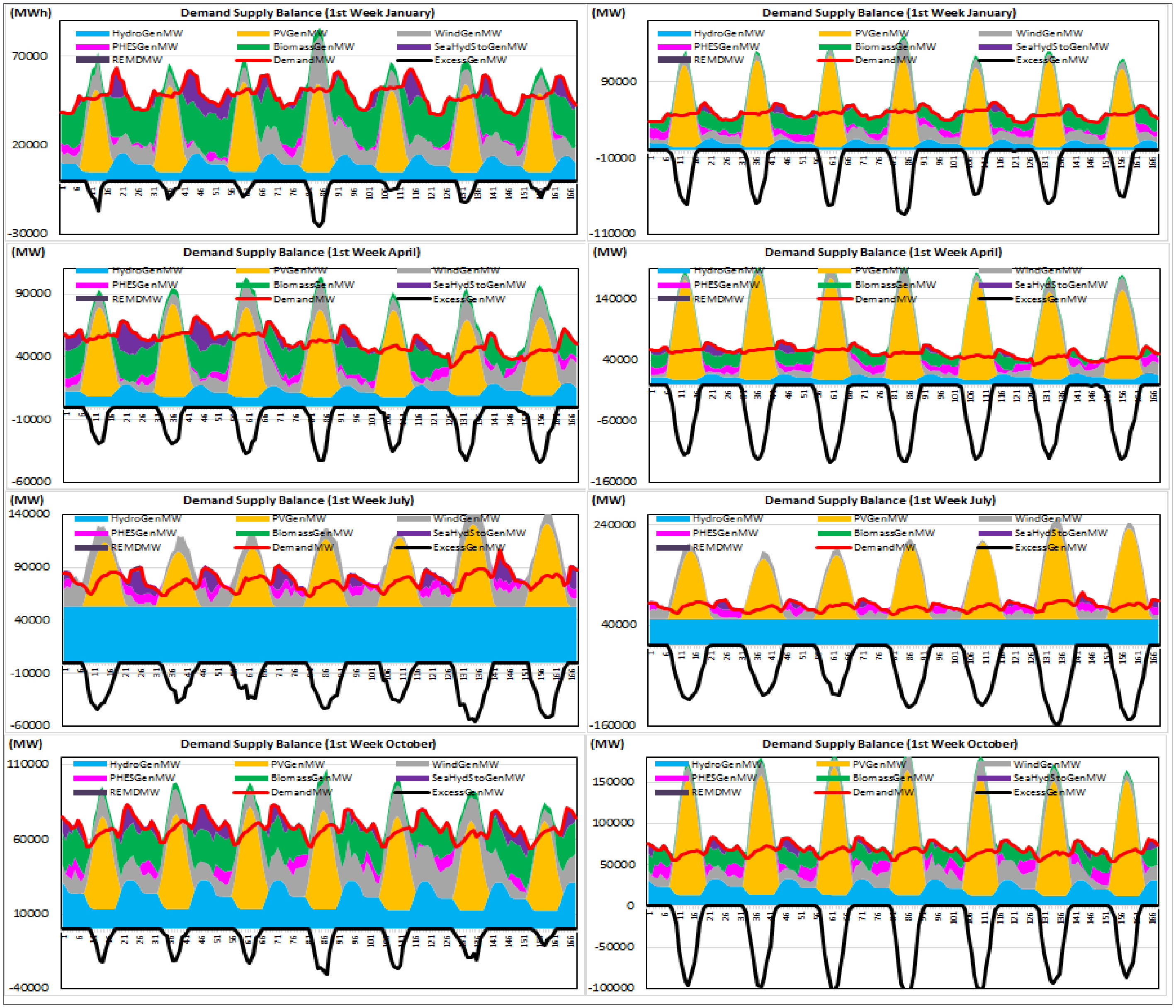




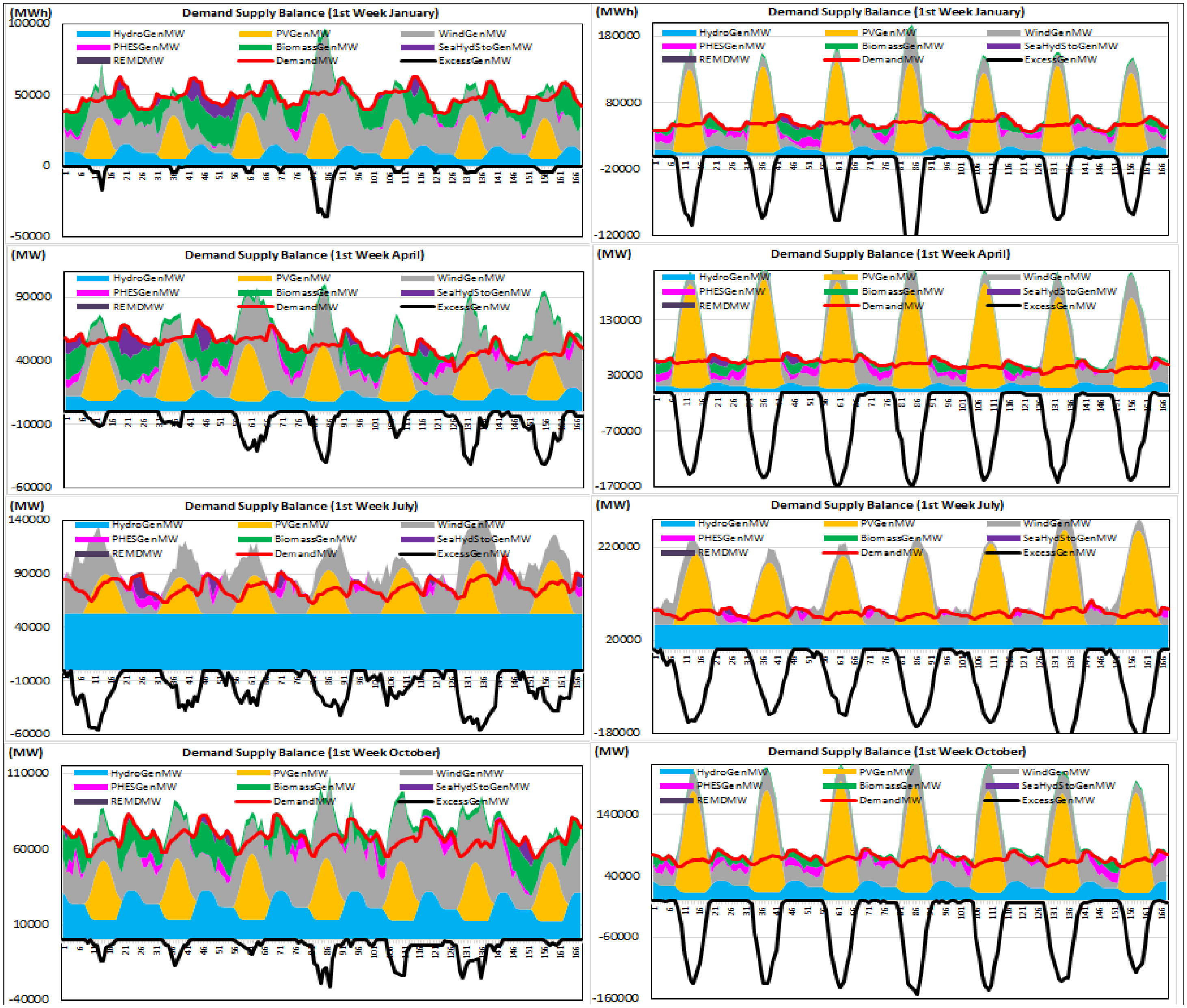




LW_Supply_Case & HG_Demand_Scenario

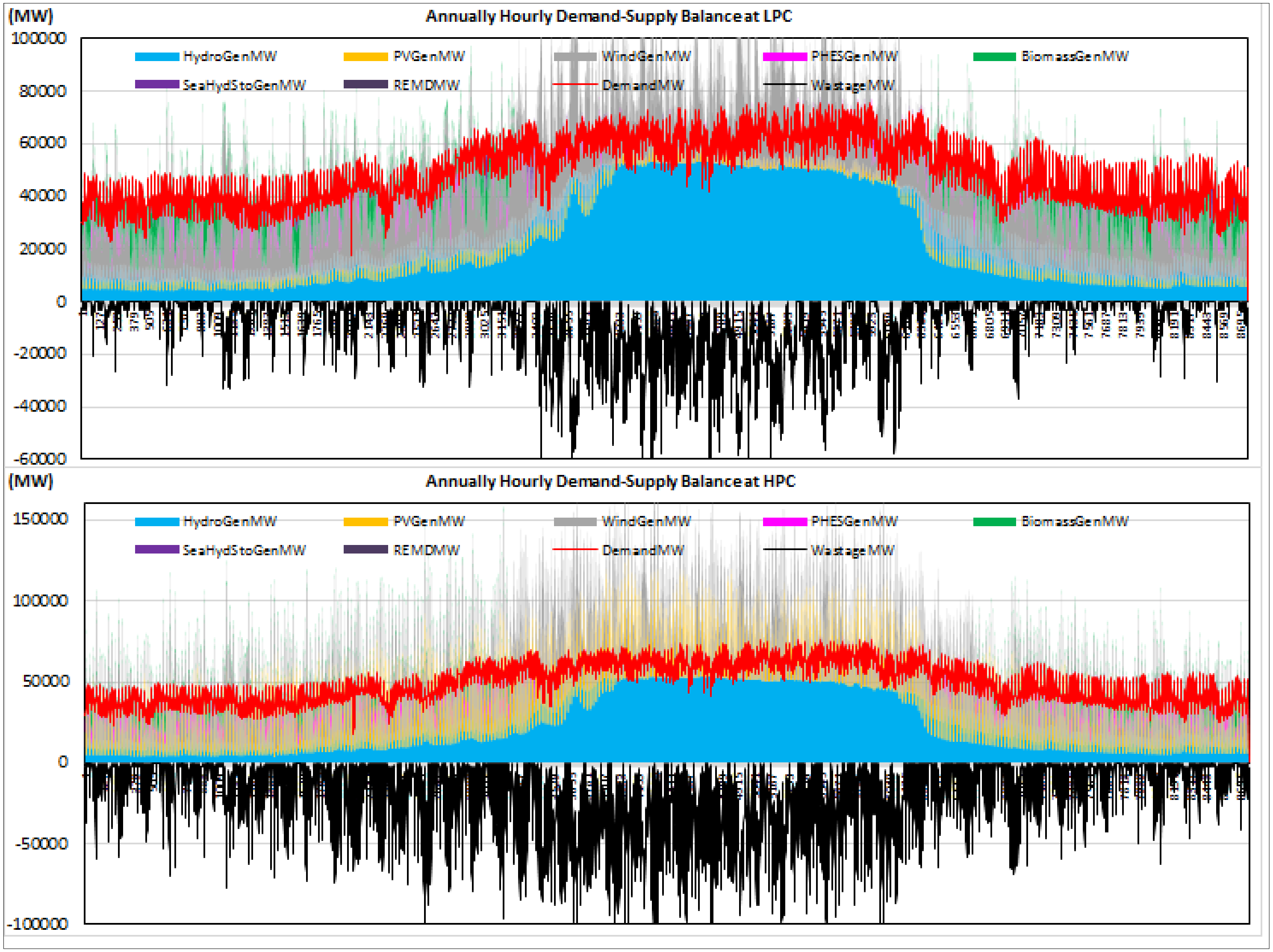


HW_Supply_Case & HG_Demand_Scenario

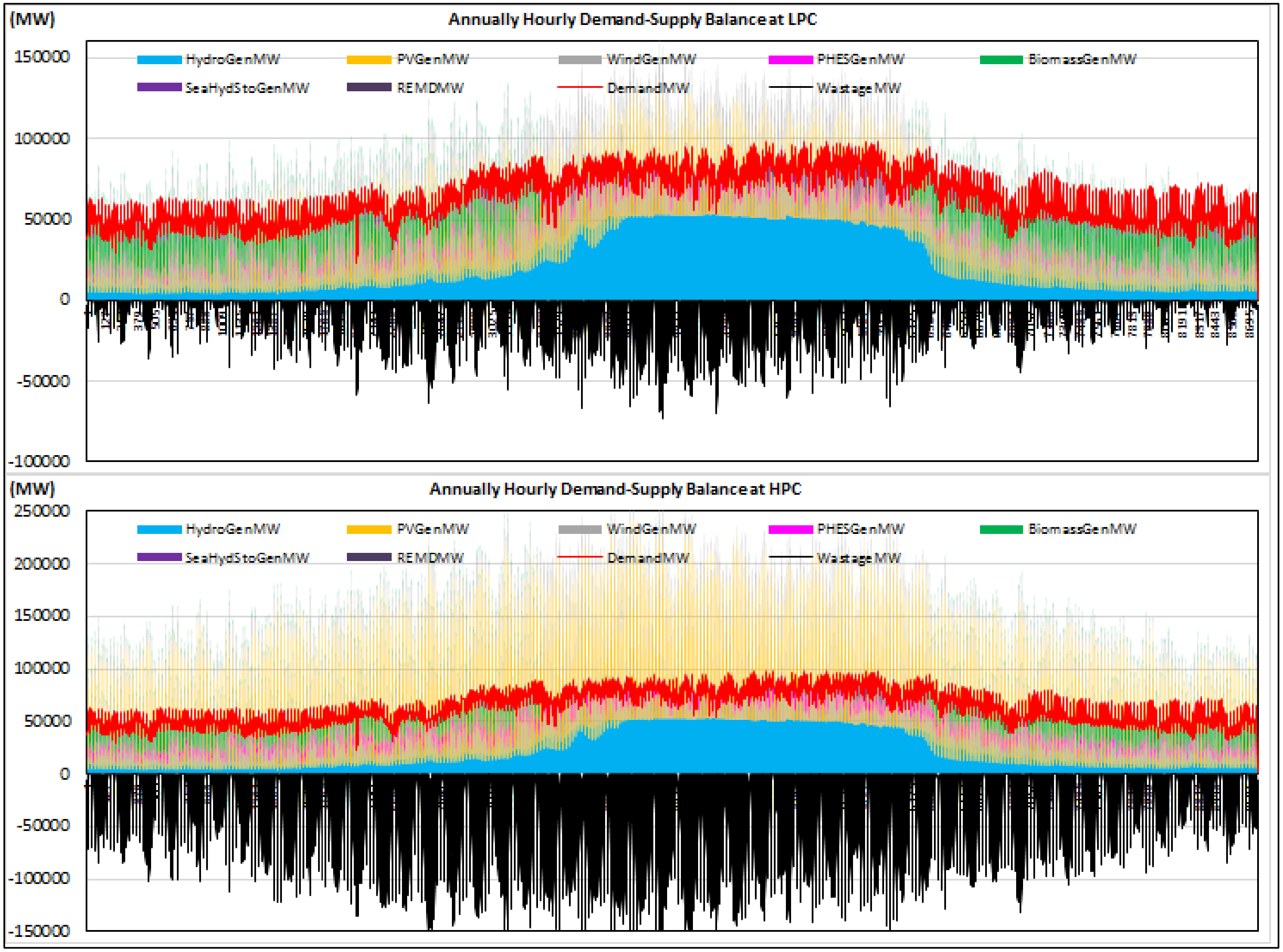


Appendix-F: Annual Hourly Demand-Supply Balance

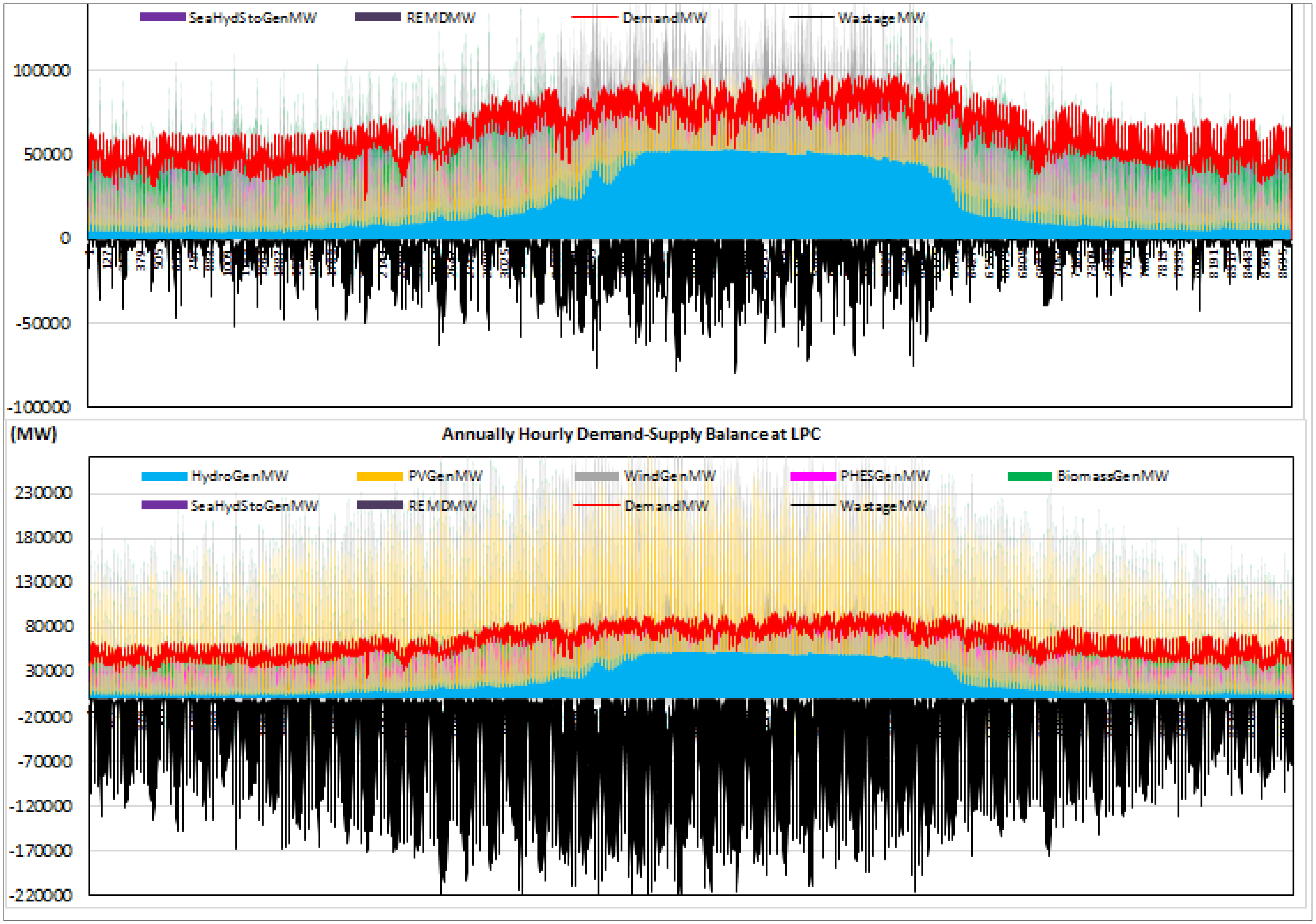
HW_Supply_Case and OG_Demand_Scenario



LW_Supply_Case & HG_Demand_Scenario

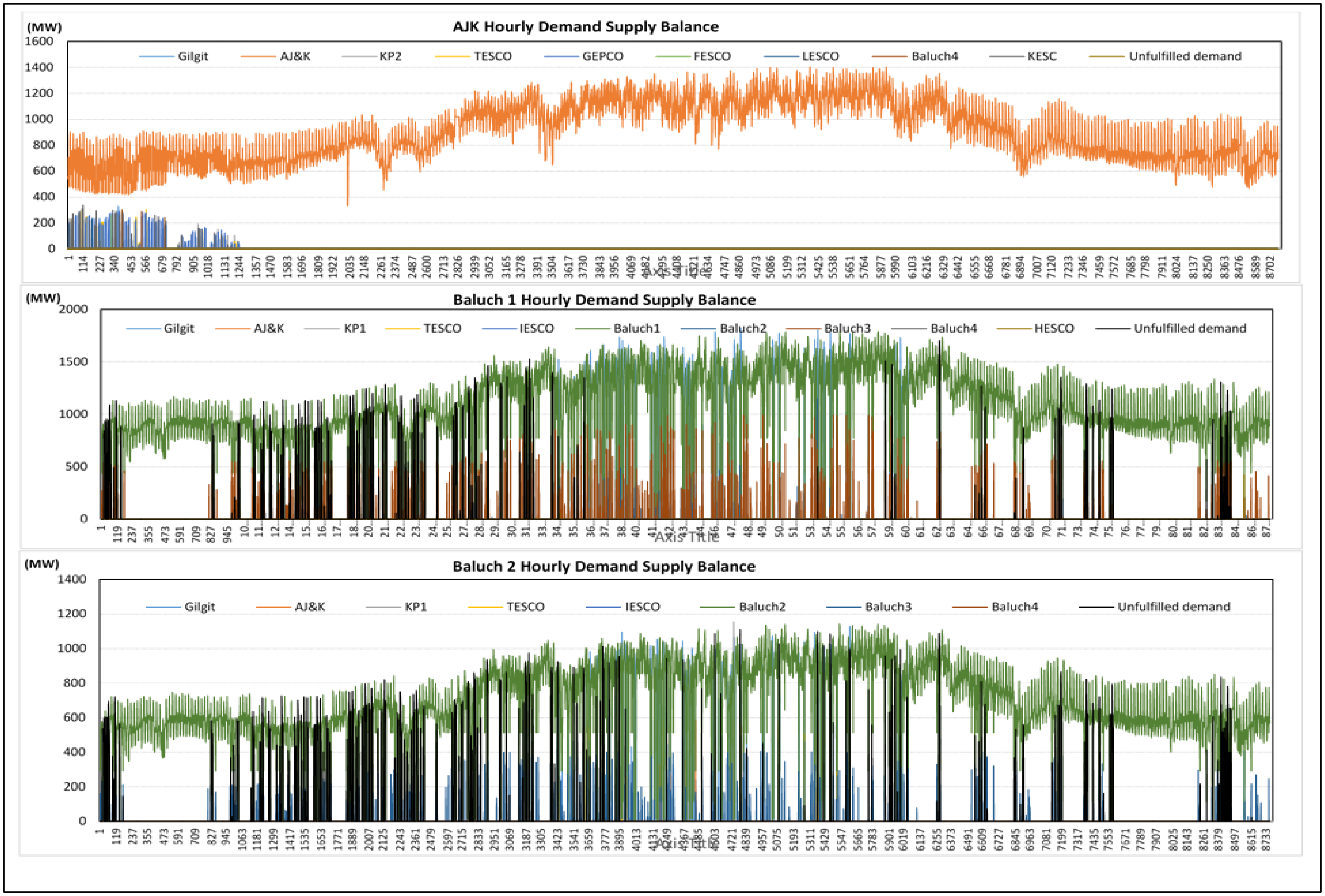


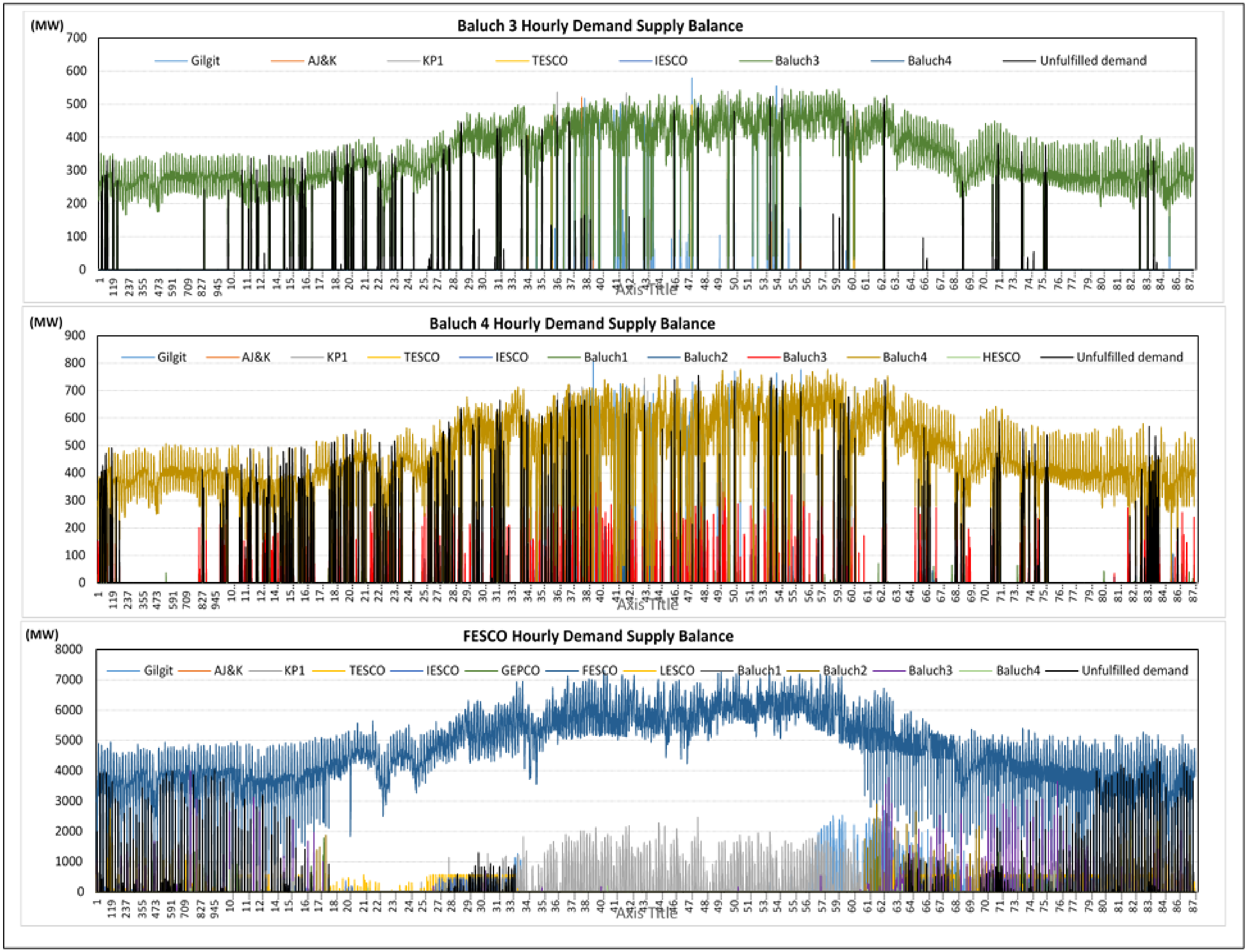
HW_Supply_Case & HG_Demand_Scenario

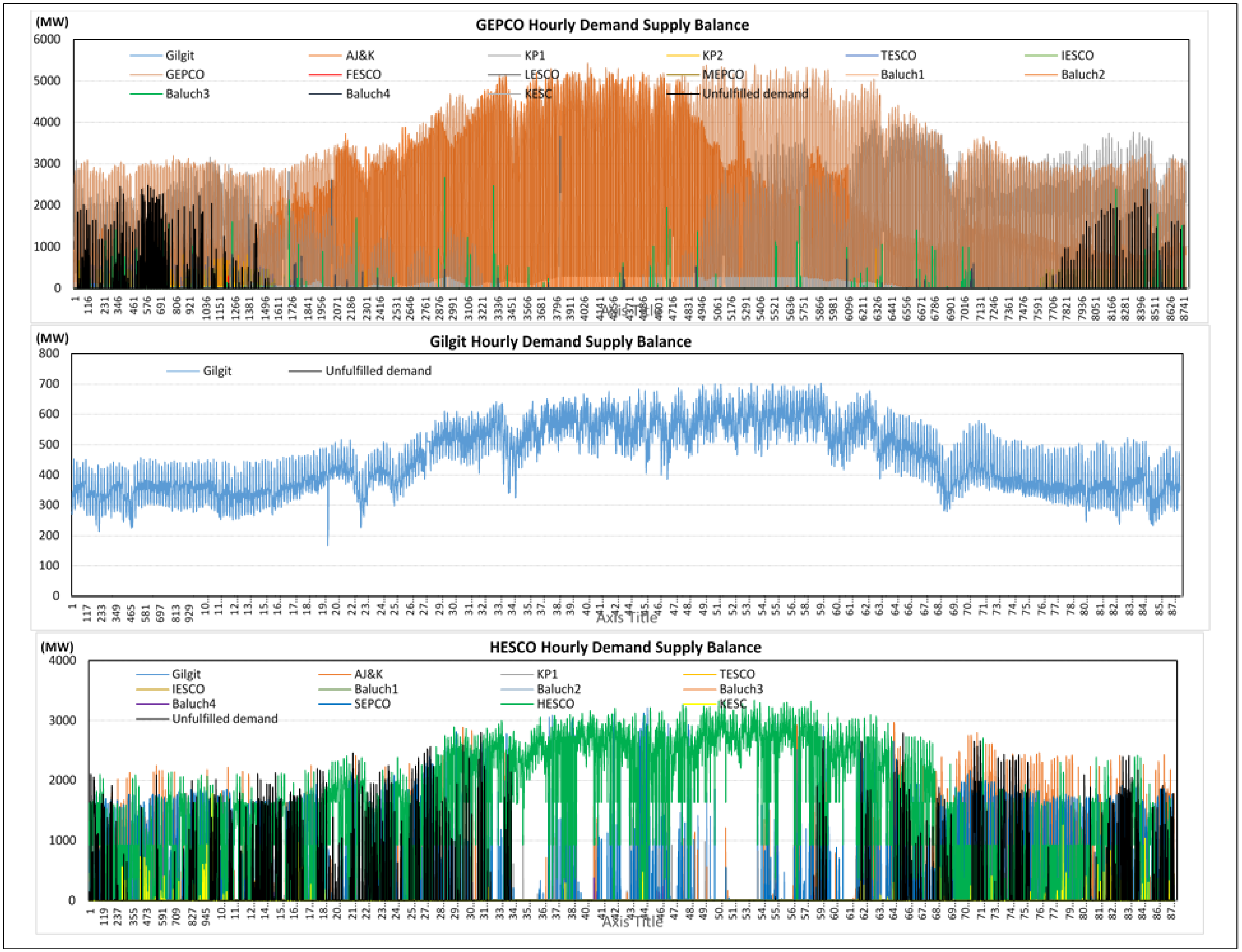


Appendix-G: Hourly Demand-Supply Balances of the Regions

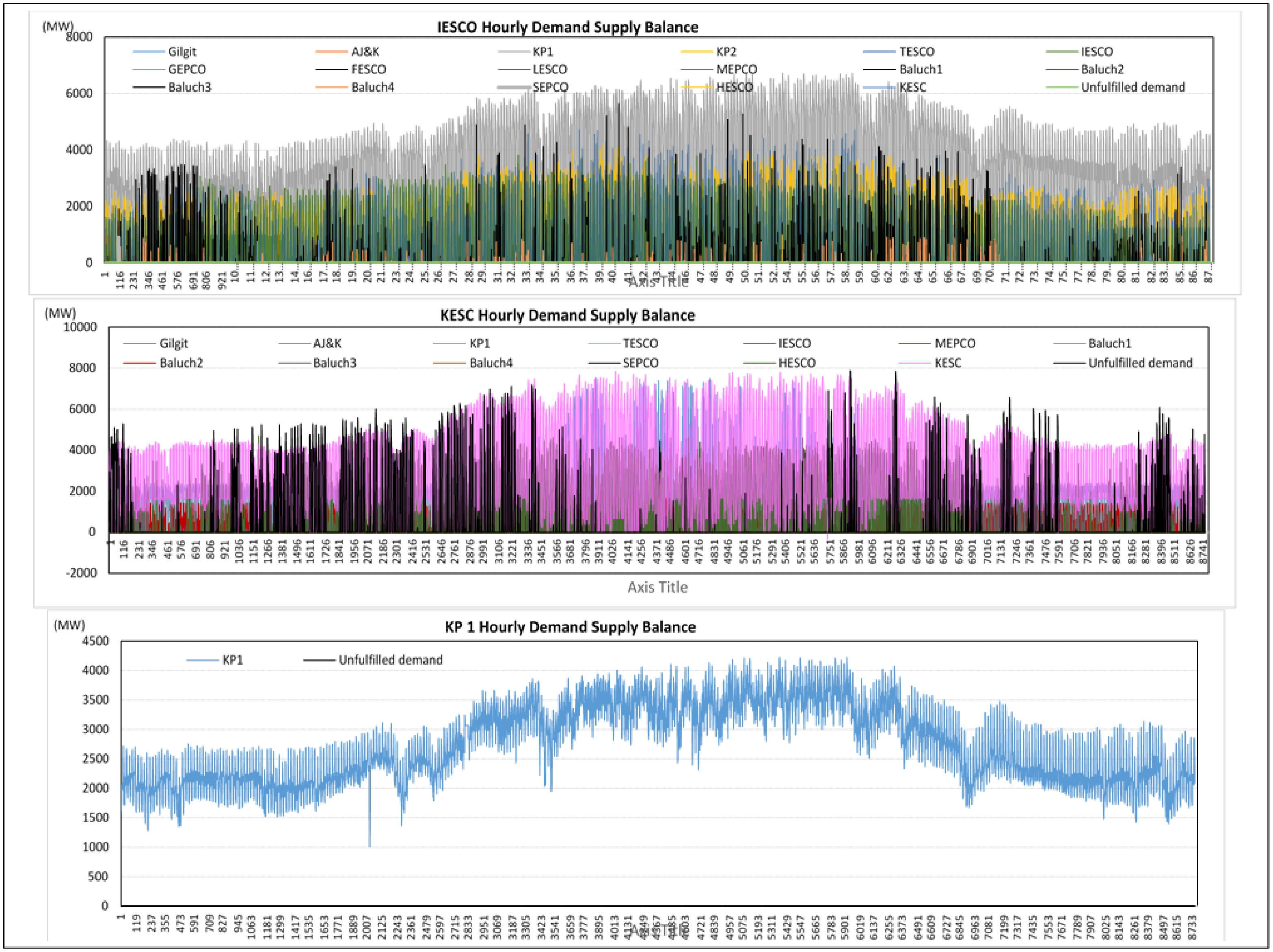
(Unfulfilled demand is equivalent to seasonal storage supply)

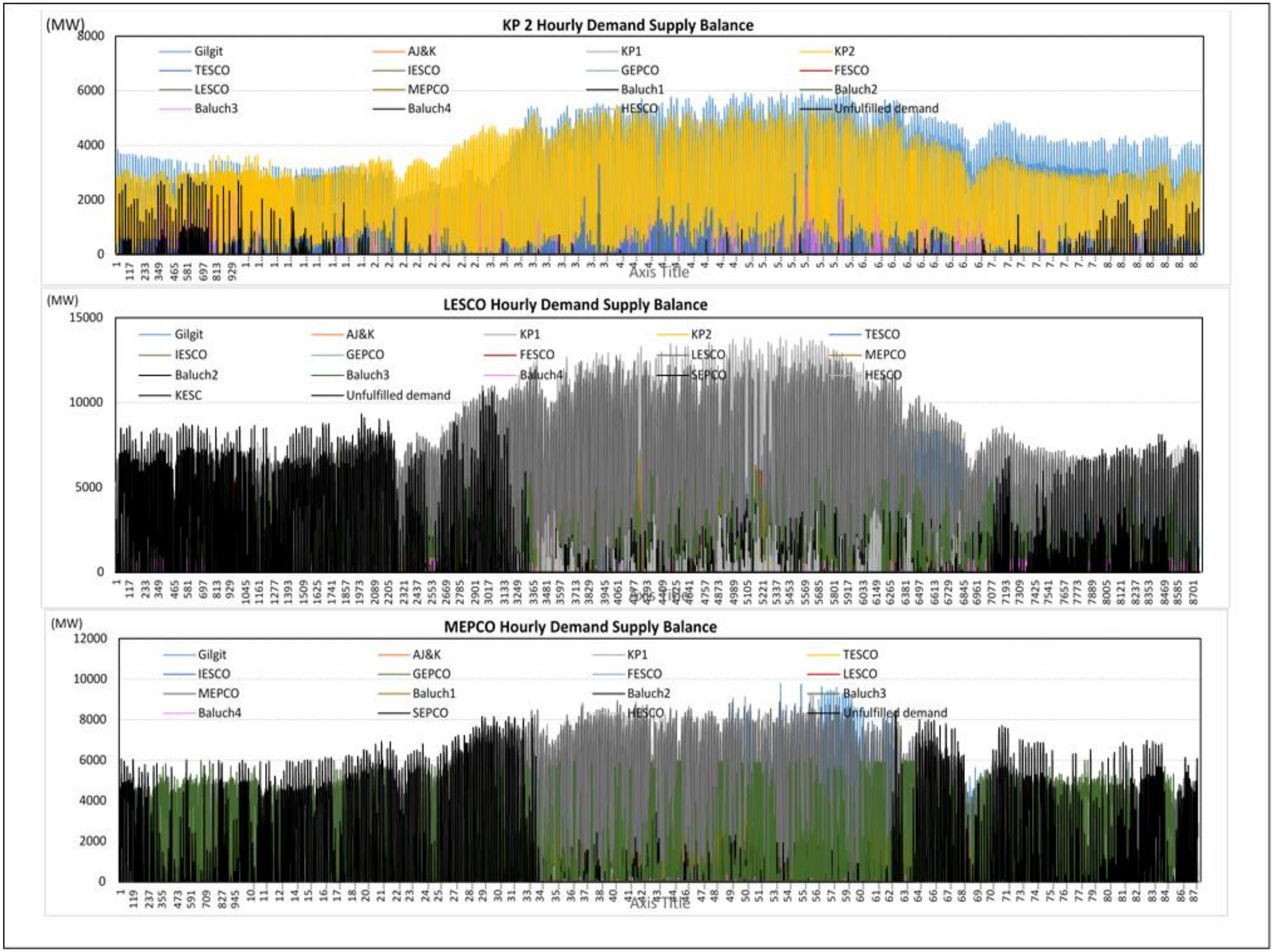


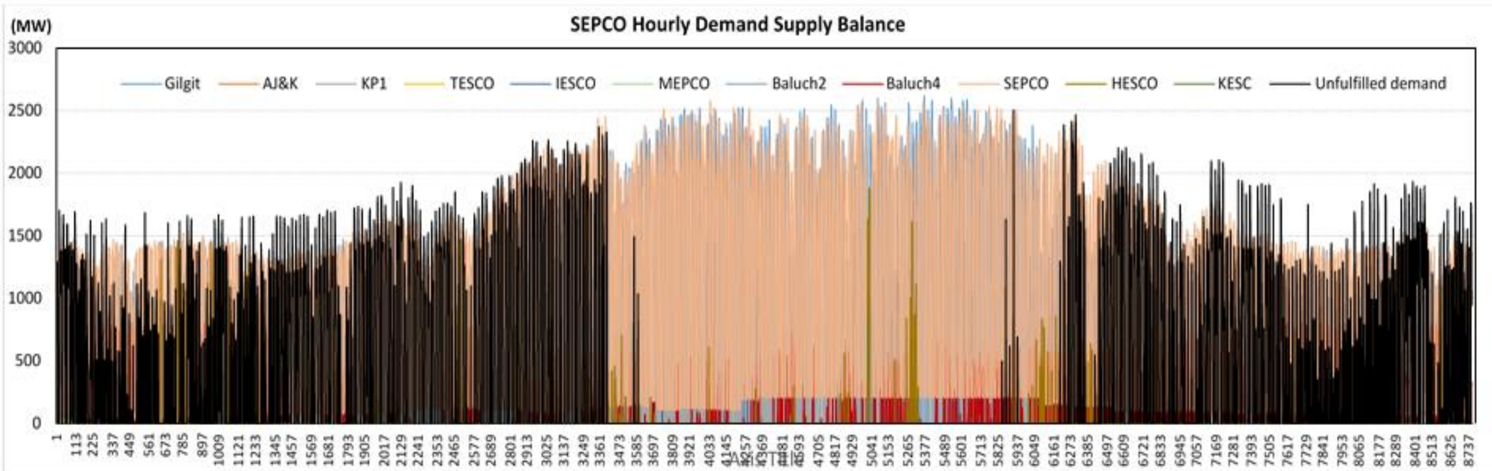

Baluch 3 Hourly Demand Supply Balance
(MW)
Gilgit
AJ&K
KP1
TESCO
IESCO
Baluch3
Baluch4
Unfulfilled demand
Axis Title
Baluch 4 Hourly Demand Supply Balance
(MW)
Gilgit
AJ&K
KP1
TESCO
IESCO
Baluch1
Baluch2
Baluch3
Baluch4
HESCO
Unfulfilled demand
Axis Title
FESCO Hourly Demand Supply Balance
(MW)
Gilgit
AJ&K
KP1
TESCO
IESCO
GEPCO
FESCO
LESCO
Baluch1
Baluch2
Baluch3
Baluch4
Unfulfilled demand
Axis Title

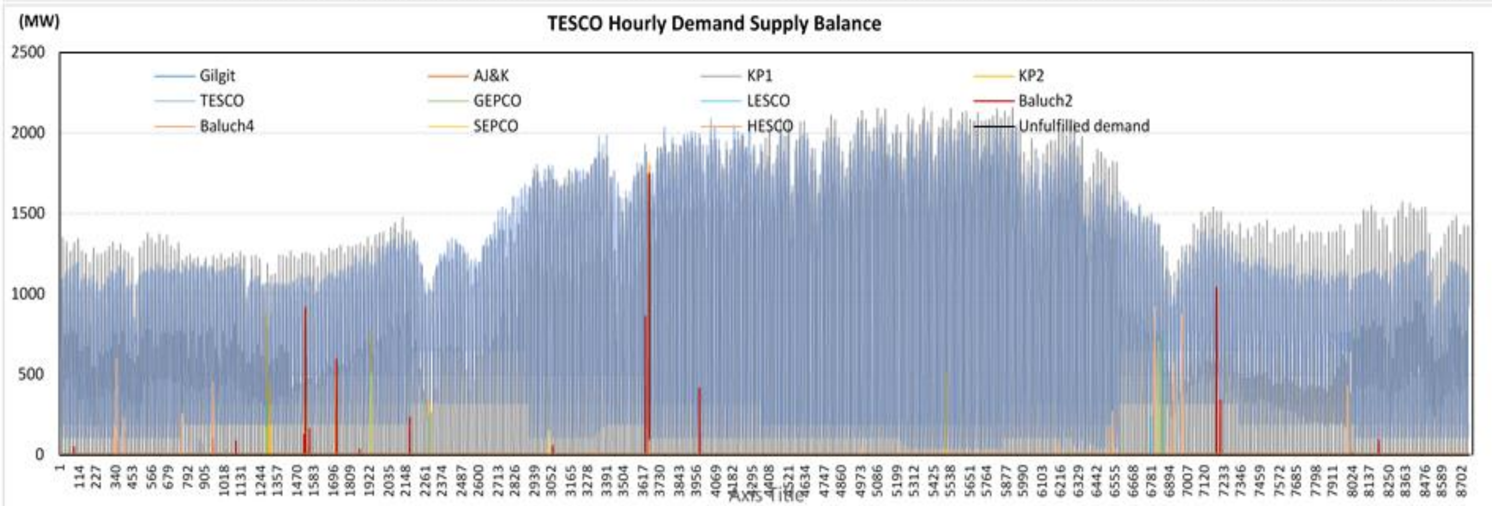


GEPCO Hourly Demand Supply Balance
(MW)
Gilgit
AJ&K
KP1
KP2
TESCO
IESCO
GEPCO
FESCO
LESCO
MEPCO
Baluch1
Baluch2
Baluch3
Baluch4
KESC
Unfulfilled demand
Axis Title
Gilgit Hourly Demand Supply Balance
(MW)
Gilgit
Unfulfilled demand
Axis Title
HESCO Hourly Demand Supply Balance
(MW)
Gilgit
AJ&K
KP1
TESCO
IESCO
Baluch1
Baluch2
Baluch3
Baluch4
SEPCO
HESCO
KESC
Unfulfilled demand
Axis Title


IESCO Hourly Demand Supply Balance
(MW)
8000
6000
4000
2000
0
Gilgit
AJ&K
KP1
KP2
TESCO
IESCO
GEPCO
FESCO
LESCO
MEPCO
Baluch1
Baluch2
Baluch3
Baluch4
SEPCO
HESCO
KESC
Unfulfilled demand
Axis Title
KESC Hourly Demand Supply Balance
(MW)
10000
8000
6000
4000
2000
0
-2000
Gilgit
AJ&K
KP1
TESCO
IESCO
MEPCO
Baluch1
Baluch2
Baluch3
Baluch4
SEPCO
HESCO
KESC
Unfulfilled demand
Axis Title
KP 1 Hourly Demand Supply Balance
(MW)
4500
4000
3500
3000
2500
2000
1500
1000
500
0
KP1
Unfulfilled demand
Axis Title


KP 2 Hourly Demand Supply Balance
(MW)
Gilgit
AJ&K
KP1
KP2
TESCO
IESCO
GEPCO
FESCO
LESCO
MEPCO
Baluch1
Baluch2
Baluch3
Baluch4
HESCO
Unfulfilled demand
Axis Title
LESCO Hourly Demand Supply Balance
(MW)
Gilgit
AJ&K
KP1
KP2
TESCO
IESCO
GEPCO
FESCO
LESCO
MEPCO
Baluch2
Baluch3
Baluch4
SEPCO
HESCO
KESC
Unfulfilled demand
MEPCO Hourly Demand Supply Balance
(MW)
Gilgit
AJ&K
KP1
TESCO
IESCO
GEPCO
FESCO
LESCO
MEPCO
Baluch1
Baluch2
Baluch3
Baluch4
SEPCO
HESCO
Unfulfilled demand
Axis Title


SEPCO Hourly Demand Supply Balance
(MW)
3000
2500
2000
1500
1000
500
0
Gilgit
AJ&K
KP1
TESCO
IESCO
MEPCO
Baluch2
Baluch4
SEPCO
HESCO
KESC
Unfulfilled demand


TESCO Hourly Demand Supply Balance
(MW)
2500
2000
1500
1000
500
0
Gilgit
AJ&K
KP1
KP2
TESCO
GEPCO
LESCO
Baluch2
Baluch4
SEPCO
HESCO
Unfulfilled demand

Appendix-H: Annual Regional Imports -Exports Including Annual Supply Storage (SS) and Transmission Losses

LW_Supply_Case and OG_Demand_Scenario at the LPC

Demand Side (TWh)	Supply Side (TWh): AJ&K	Baluch1	Baluch2	Baluch3	Baluch4	FESCO	GEPCO	Gilgit	HESCO	IESCO	KESC	KP1	KP2	LESCO	MEPCO	SEPCO	TESCO	SS	Daily Storage Use	Total
Baluch3	0.00	0.08	0.00	2.87	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.14		3.11
Gilgit	0.00	0.02	0.03	0.60	0.10	0.00	0.00	5.37	0.02	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	2.14	4.01
Baluch4	0.00	0.37	0.00	0.10	3.48	0.00	0.00	0.08	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.45		4.49
Baluch2	0.01	0.73	5.09	0.15	0.00	0.00	0.00	0.10	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50		6.58
AJ&K	7.98	0.04	0.05	0.43	0.03	0.00	0.00	0.08	0.09	0.00	0.00	0.16	0.00	0.00	0.00	0.00	0.00	0.00	0.89	7.98
Baluch1	0.00	8.39	0.63	0.81	0.00	0.00	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33		10.28
TESCO	0.00	0.00	0.01	0.15	0.04	0.00	0.00	0.40	0.00	0.00	0.00	6.94	0.02	0.00	0.00	0.00	4.94	0.81	0.59	12.73
SEPCO	0.07	0.01	1.39	0.00	1.83	0.00	0.00	2.29	0.89	0.01	0.00	0.65	0.00	0.00	0.00	2.88	0.06	5.75		15.83
HESCO	0.00	0.57	0.33	1.83	0.06	0.00	0.00	0.27	13.00	0.07	0.00	0.07	0.00	0.00	0.00	0.00	0.01	2.88		19.11
KP1	0.00	0.01	0.03	0.53	0.10	0.00	0.00	0.48	0.12	0.00	0.00	24.72	0.00	0.00	0.00	0.00	0.00	0.00	1.98	24.00
KP2	16.10	0.00	0.00	0.04	0.03	0.00	6.71	1.33	0.00	0.14	0.00	5.16	0.00	0.00	0.00	0.00	0.00	3.65		33.18
GEPCO	0.00	0.00	0.00	0.01	0.01	0.00	0.00	21.76	0.00	0.00	0.00	0.32	9.54	0.00	0.00	0.00	0.06	1.71		33.40
IESCO	0.00	0.00	0.02	0.21	0.03	0.00	0.00	1.50	0.04	11.93	0.00	24.71	0.00	0.00	0.00	0.00	0.00	0.04	0.65	37.85
FESCO	0.04	0.08	0.09	2.03	0.06	28.50	0.00	1.95	0.02	0.40	0.00	1.29	0.00	0.00	0.00	0.00	0.09	9.52		44.08
KESC	0.08	6.96	2.25	6.90	0.08	0.00	0.00	1.31	9.41	0.11	14.20	0.27	0.00	0.00	0.00	0.00	0.10	6.61		48.29
MEPCO	0.20	3.82	0.65	10.89	0.01	0.00	0.00	8.70	0.09	0.04	0.00	7.23	0.00	0.00	5.48	0.00	0.09	17.67		54.87
LESCO	5.51	0.00	0.01	1.82	0.21	0.88	0.00	9.67	0.17	0.01	0.00	25.68	0.00	9.27	0.00	0.00	0.01	24.68		77.92

LW_Supply_Case and OG_Demand_Scenario at the HPC

Demand Side (TWh)	Supply Side (TWh): AJ&K	Baluch1	Baluch2	Baluch3	Baluch4	FESCO	GEPCO	Gilgit	HESCO	IESCO	KESC	KP1	KP2	LESCO	MEPCO	SEPCO	TESCO	SS	Daily Storage Use	Total
Baluch3	0.00	0.08	0.00	2.87	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.13		3.12
Gilgit	0.00	0.03	0.02	0.17	0.01	0.00	0.00	11.23	0.01	0.09	0.00	0.35	0.02	0.00	0.00	0.00	0.00	0.00	7.97	3.97
Baluch4	0.00	0.36	0.07	0.14	5.51	0.00	0.00	0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	1.76	4.44
Baluch2	0.01	0.59	5.28	0.12	0.06	0.00	0.00	0.10	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.43		6.60
AJ&K	10.30	0.05	0.03	0.16	0.01	0.00	0.13	0.03	0.03	0.38	0.07	0.06	0.09	0.05	0.01	0.02	0.01	0.00	3.48	7.95
Baluch1	0.00	8.52	0.57	0.75	0.00	0.00	0.00	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.32		10.29
TESCO	0.00	0.01	0.01	0.06	0.01	0.00	0.00	0.16	0.00	0.02	0.00	4.87	0.29	0.00	0.00	0.00	10.33	0.00	3.11	12.65
SEPCO	0.15	0.00	0.42	0.00	1.31	0.00	0.00	1.79	0.41	0.00	0.01	0.29	0.00	0.00	0.03	7.06	0.11	4.27		15.85
HESCO	0.00	0.19	0.15	1.30	0.12	0.00	0.00	0.21	14.43	0.08	0.02	0.05	0.00	0.00	0.00	0.02	0.02	2.54		19.15
KP1	0.00	0.01	0.02	0.12	0.00	0.00	0.00	0.07	0.06	0.08	0.01	28.43	0.01	0.00	0.00	0.00	0.01	0.00	4.88	23.94
GEPCO	12.40	0.00	0.00	0.02	0.01	0.00	12.97	1.20	0.00	0.63	0.00	5.37	0.00	0.01	0.00	0.00	0.06	0.48		33.14
KP2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	15.76	0.00	0.00	0.00	0.24	16.63	0.00	0.00	0.00	0.55	0.08		33.25
IESCO	0.00	0.01	0.01	0.05	0.00	0.00	0.00	0.74	0.02	18.22	0.00	19.91	0.06	0.00	0.00	0.00	0.00	0.00	1.34	37.68
FESCO	0.03	0.01	0.01	0.50	0.01	35.15	0.00	1.19	0.00	1.30	0.00	0.27	0.00	0.05	0.00	0.00	0.98	4.61		44.12
KESC	0.15	3.39	1.35	5.33	0.61	0.00	0.00	0.97	5.99	0.12	24.19	0.25	0.00	0.00	0.03	0.05	0.22	5.58		48.22
MEPCO	0.75	1.27	0.14	6.12	0.01	0.35	0.01	7.69	0.06	0.02	0.00	2.64	0.00	0.09	21.31	0.00	0.17	14.08		54.73
LESCO	2.54	0.00	0.00	0.78	0.09	1.32	0.03	10.58	0.05	0.31	0.00	16.99	0.01	31.04	0.11	0.00	0.10	14.16		78.12

HW_Supply_Case and OG_Demand_Scenario at the LPC

Demand Side (TWh)	Supply Side (TWh)																		Daily Storage Use	Total
		AJ&K	Baluch1	Baluch2	Baluch3	Baluch4	FESCO	GEPCO	Gilgit	HESCO	IESCO	KESC	KP1	KP2	LESCO	MEPCO	SEPCO	TESCO	SS		
	Baluch3	0.00	0.19	0.00	2.79	0.00	0.00	0.00	0.03	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07		3.11
	Gilgit	0.00	0.11	0.17	2.10	0.12	0.00	0.00	4.93	0.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.60	3.99
	Baluch4	0.00	0.59	0.00	0.15	4.33	0.00	0.00	0.06	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22	0.92	4.57
	Baluch2	0.00	0.95	5.14	0.08	0.01	0.00	0.00	0.07	0.11	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22		6.59
	AJ&K	7.96	0.15	0.14	1.17	0.03	0.00	0.00	0.06	0.28	0.00	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.01	1.88	7.98
	Baluch1	0.00	8.26	1.15	0.55	0.00	0.00	0.00	0.07	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.15		10.28
	TESCO	0.00	0.01	0.03	0.70	0.26	0.00	0.00	0.41	0.04	0.00	0.00	7.44	0.03	0.00	0.00	0.00	4.29	0.66	1.12	12.76
	SEPCO	0.05	0.12	2.69	0.00	2.00	0.00	0.00	1.11	4.81	0.00	0.03	0.21	0.00	0.00	0.00	1.64	0.04	3.68		16.38
	HESCO	0.00	1.99	0.82	1.46	0.08	0.00	0.00	0.14	13.31	0.03	0.20	0.03	0.00	0.00	0.00	0.00	0.01	1.18		19.24
	KP1	0.00	0.01	0.06	1.91	0.17	0.00	0.00	0.37	0.77	0.00	0.00	24.18	0.00	0.00	0.00	0.00	0.00	0.00	3.48	23.99
	GEPCO	17.71	0.02	0.00	0.86	0.10	0.00	2.24	1.36	0.02	0.13	0.00	8.28	0.00	0.00	0.00	0.00	0.00	2.92		33.64
	KP2	0.00	0.00	0.00	0.54	0.08	0.00	0.00	20.30	0.01	0.00	0.00	0.25	10.15	0.00	0.00	0.00	0.22	2.09		33.65
	IESCO	0.00	0.00	0.04	0.47	0.03	0.00	0.00	2.55	0.12	5.75	0.00	29.58	0.00	0.00	0.00	0.00	0.00	0.19	0.68	38.03
	FESCO	0.03	0.60	0.37	3.35	0.09	29.36	0.00	1.98	0.25	0.23	0.01	0.59	0.00	0.00	0.00	0.00	0.31	7.42		44.58
	KESC	0.04	6.35	2.28	2.60	0.14	0.00	0.00	0.37	13.85	0.03	20.44	0.09	0.00	0.00	0.00	0.00	0.08	1.91		48.19
	MEPCO	0.19	11.44	3.55	16.42	0.09	0.00	0.00	4.92	1.97	0.01	0.01	4.24	0.00	0.00	2.98	0.00	0.05	9.86		55.73
	LESCO	2.59	0.00	0.48	7.20	0.30	1.42	0.00	12.11	1.91	0.04	0.00	32.41	0.02	4.14	0.00	0.00	0.03	17.54		80.19

HW_Supply_Case and OG_Demand_Scenario at the HPC

Demand Side (TWh)	Supply Side (TWh)																		Daily Storage Use	Total
		AJ&K	Baluch1	Baluch2	Baluch3	Baluch4	FESCO	GEPCO	Gilgit	HESCO	IESCO	KESC	KP1	KP2	LESCO	MEPCO	SEPCO	TESCO	SS		
	Baluch3	0.00	0.18	0.00	2.83	0.00	0.00	0.00	0.02	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05		3.11
	Gilgit	0.00	0.25	0.12	0.81	0.03	0.00	0.00	7.26	0.17	0.01	0.04	0.27	0.04	0.26	0.19	0.02	0.00	0.00	5.43	4.05
	Baluch4	0.00	0.67	0.06	0.10	4.70	0.00	0.00	0.03	0.09	0.00	0.04	0.00	0.00	0.00	0.00	0.01	0.00	0.01	1.27	4.45
	Baluch2	0.00	0.79	5.39	0.06	0.03	0.00	0.00	0.05	0.09	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.13		6.56
	AJ&K	8.85	0.15	0.04	0.39	0.01	0.00	0.06	0.00	0.09	0.01	0.21	0.02	0.05	0.52	0.35	0.02	0.00	0.00	2.78	7.97
	Baluch1	0.00	8.68	0.92	0.42	0.00	0.00	0.00	0.05	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.11		10.27
	TESCO	0.10	0.03	0.06	0.26	0.11	0.00	0.00	0.30	0.07	0.00	0.12	7.08	1.00	0.10	0.12	0.02	5.46	0.01	2.08	12.75
	SEPCO	0.06	0.07	1.55	0.00	1.56	0.00	0.00	0.71	2.92	0.00	0.04	0.20	0.00	0.00	0.04	6.81	0.05	1.94		15.95
	HESCO	0.00	1.28	0.51	1.03	0.10	0.00	0.00	0.07	14.06	0.02	0.59	0.04	0.00	0.00	0.08	0.58	0.01	0.82		19.20
	KP1	0.00	0.16	0.07	0.66	0.05	0.00	0.03	0.08	0.35	0.01	0.26	27.06	0.01	0.67	0.46	0.04	0.00	0.00	5.96	23.96
	GEPCO	12.86	0.00	0.02	0.44	0.05	0.00	11.73	0.75	0.02	0.30	0.01	6.45	0.00	0.24	0.01	0.00	0.00	0.28		33.15
	KP2	0.01	0.00	0.01	0.26	0.02	0.00	0.00	15.87	0.01	0.00	0.00	0.21	16.29	0.02	0.02	0.00	0.43	0.10		33.27
	IESCO	0.00	0.03	0.02	0.15	0.01	0.02	0.09	1.12	0.11	14.94	0.07	21.81	0.17	0.24	0.01	0.00	0.00	0.00	1.03	37.76
	FESCO	0.44	0.36	0.21	1.27	0.04	31.35	0.68	1.78	0.12	1.22	0.08	1.26	0.00	2.43	0.01	0.00	0.72	2.57		44.53
	KESC	0.04	4.33	1.52	1.94	0.17	0.00	0.00	0.21	9.71	0.02	28.34	0.12	0.00	0.01	0.07	0.02	0.05	1.27		47.81
	MEPCO	0.45	6.57	1.92	10.20	0.09	0.05	0.00	3.67	1.21	0.01	0.01	3.00	0.00	0.03	21.39	0.00	0.12	6.70		55.42
	LESCO	2.76	0.00	0.23	3.87	0.14	1.33	0.01	10.03	0.92	0.07	0.01	23.11	0.02	29.79	0.26	0.01	0.07	5.99		78.65

LW_Supply_Case and HG_Demand_Scenario at the LPC

Demand Side (TWh)	Supply Side(TWh) AJ&K	Baluch1	Baluch2	Baluch3	Baluch4	FESCO	GEPCO	Gilgit	HESCO	IESCO	KESC	KP1	KP2	LESCO	MEPCO	SEPCO	TESCO	SS	Daily Storage Use	Total
LESCO	3.37	0.00	0.08	0.98	0.18	0.49	0.00	17.14	0.75	1.61	0.00	19.76	0.00	20.30	0.00	0.35	0.00	35.56		100.58
MEPCO	0.69	10.61	0.63	6.79	0.06	0.00	0.00	5.54	0.05	0.07	0.00	4.03	0.00	0.02	11.99	0.00	0.51	30.31		71.32
KESC	0.01	4.78	1.49	8.25	0.52	0.00	0.00	0.22	10.72	0.05	21.61	0.05	0.00	0.00	0.00	0.18	0.08	14.44		62.41
FESCO	0.18	0.66	0.36	1.44	0.15	34.09	0.00	2.81	0.03	2.85	0.00	1.12	0.00	0.00	0.00	0.00	0.62	12.94		57.25
IESCO	0.00	0.01	0.03	0.09	0.01	0.00	0.00	3.36	0.34	19.93	0.00	26.28	0.01	0.00	0.00	0.00	0.00	0.06	1.19	48.94
KP2	0.00	0.00	0.00	0.02	0.01	0.00	0.00	25.22	0.00	0.01	0.00	0.20	12.67	0.00	0.00	0.00	1.44	3.62		43.19
GEPCO	18.29	0.00	0.00	0.09	0.03	0.00	7.48	2.39	0.00	1.43	0.00	6.76	0.00	0.00	0.00	0.00	0.03	6.47		42.98
KP1	0.00	0.15	0.10	0.57	0.09	0.00	0.00	1.02	1.57	0.09	0.02	34.62	0.00	0.00	0.00	0.16	0.00	0.00	6.91	31.49
HESCO	0.00	0.04	0.07	1.30	0.11	0.00	0.00	0.04	18.16	0.05	0.00	0.01	0.00	0.00	0.00	0.00	0.01	4.88		24.67
SEPCO	0.04	0.00	0.32	0.00	1.17	0.00	0.00	0.59	0.24	0.00	0.00	0.17	0.00	0.00	0.00	8.41	0.12	9.37		20.43
TESCO	0.00	0.12	0.09	0.28	0.05	0.00	0.00	0.98	0.16	0.04	0.05	7.73	0.03	0.00	0.00	0.02	8.86	0.75	2.64	16.50
Baluch1	0.00	10.66	0.63	1.24	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.76		13.31
AJ&K	10.38	0.18	0.16	0.54	0.03	0.00	0.00	0.19	0.33	0.37	0.07	0.24	0.00	0.00	0.00	1.10	0.00	0.00	3.03	10.56
Baluch2	0.00	0.79	6.52	0.21	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.97		8.51
Baluch4	0.00	0.37	0.00	0.20	6.02	0.00	0.00	0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.38	1.17	5.87
Gilgit	0.00	0.41	0.24	0.86	0.11	0.00	0.00	10.71	0.25	0.06	0.00	0.03	0.00	0.00	0.00	0.04	0.00	0.00	7.17	5.54
Baluch3	0.00	0.08	0.00	3.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.24		4.02

LW_Supply_Case and HG_Demand_Scenario at the HPC

Demand Side (TWh)	Supply Side (TWh) AJ&K	Baluch1	Baluch2	Baluch3	Baluch4	ESCO	GEPCO	Gilgit	HESCO	IESCO	KESC	KP1	KP2	LESCO	MEPCO	SEPCO	TESCO	SS	Daily Storage Use	Total
ESCO	3.37	0.00	0.08	0.98	0.18	0.49	0.00	17.14	0.75	1.61	0.00	9.76	0.00	20.30	0.00	0.35	0.00	35.56		100.58
MEPCO	0.69	10.61	0.63	6.79	0.06	0.00	0.00	5.54	0.05	0.07	0.00	4.03	0.00	0.02	11.99	0.00	0.51	30.31		71.32
ESC	0.01	4.78	1.49	8.25	0.52	0.00	0.00	0.22	10.72	0.05	21.61	0.05	0.00	0.00	0.00	0.18	0.08	14.44		62.41
ESCO	0.18	0.66	0.36	1.44	0.15	34.09	0.00	2.81	0.03	2.85	0.00	1.12	0.00	0.00	0.00	0.00	0.62	12.94		57.25
ESCO	0.00	0.01	0.03	0.09	0.01	0.00	0.00	3.36	0.34	19.93	0.00	26.28	0.01	0.00	0.00	0.00	0.00	0.06	1.19	48.94
P2	0.00	0.00	0.00	0.02	0.01	0.00	0.00	25.22	0.00	0.01	0.00	0.20	12.67	0.00	0.00	0.00	1.44	3.62		43.19
GEPCO	18.29	0.00	0.00	0.09	0.03	0.00	7.48	2.39	0.00	1.43	0.00	6.76	0.00	0.00	0.00	0.00	0.03	6.47		42.98
P1	0.00	0.15	0.10	0.57	0.09	0.00	0.00	1.02	1.57	0.09	0.02	34.62	0.00	0.00	0.00	0.16	0.00	0.00	6.91	31.49
HESCO	0.00	0.04	0.07	1.30	0.11	0.00	0.00	0.04	18.16	0.05	0.00	0.01	0.00	0.00	0.00	0.00	0.01	4.88		24.67
EPCO	0.04	0.00	0.32	0.00	1.17	0.00	0.00	0.59	0.24	0.00	0.00	0.17	0.00	0.00	0.00	8.41	0.12	9.37		20.43
ESCO	0.00	0.12	0.09	0.28	0.05	0.00	0.00	0.98	0.16	0.04	0.05	7.73	0.03	0.00	0.00	0.02	8.86	0.75	2.64	16.50
aluch1	0.00	10.66	0.63	1.24	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.76		13.31
J&K	10.38	0.18	0.16	0.54	0.03	0.00	0.00	0.19	0.33	0.37	0.07	0.24	0.00	0.00	0.00	1.10	0.00	0.00	3.03	10.56
aluch2	0.00	0.79	6.52	0.21	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.97		8.51
aluch4	0.00	0.37	0.00	0.20	6.02	0.00	0.00	0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.38	1.17	5.87
Gilgit	0.00	0.41	0.24	0.86	0.11	0.00	0.00	10.71	0.25	0.06	0.00	0.03	0.00	0.00	0.00	0.04	0.00	0.00	7.17	5.54
aluch3	0.00	0.08	0.00	3.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.24		4.02

HW_Supply_Case and HG_Demand_Scenario at the LPC

Demand Side (TWh)	Supply Side (TWh): AJ&K	Baluch1	Baluch2	Baluch3	Baluch4	FESCO	GEPCO	Gilgit	HESCO	IESCO	KESC	KP1	KP2	LESCO	MEPCO	SEPCO	TESCO	SS	Daily Storage Use	Total
LESCO	5.30	0.00	0.31	6.16	0.41	0.33	0.00	18.91	1.13	0.20	0.00	24.74	0.11	19.40	0.23	0.01	0.03	24.41		101.67
MEPCO	0.42	9.27	2.23	15.64	0.10	0.00	0.00	3.46	0.94	0.05	0.00	2.82	0.00	0.00	18.66	0.00	0.28	17.98		71.84
KESC	0.01	8.67	2.64	4.44	0.24	0.00	0.00	0.17	15.89	0.01	26.16	0.03	0.00	0.00	0.02	0.02	0.02	3.93		62.26
FESCO	0.32	0.95	0.54	3.11	0.09	33.96	0.02	3.86	0.05	1.92	0.01	2.62	0.01	0.00	0.00	0.00	0.83	9.35		57.63
IESCO	0.00	0.07	0.09	0.28	0.02	0.00	0.00	2.98	0.14	19.26	0.01	26.93	0.18	0.00	0.00	0.00	0.00	0.07	0.98	49.05
KP2	0.00	0.00	0.00	0.21	0.05	0.00	0.00	20.41	0.00	0.00	0.00	0.24	19.43	0.00	0.00	0.00	0.40	2.32		43.06
GEPCO	16.54	0.00	0.00	0.50	0.11	0.00	10.72	1.93	0.01	0.47	0.00	9.40	0.00	0.00	0.00	0.00	0.03	3.29		43.00
KP1	0.00	0.43	0.29	1.56	0.13	0.00	0.00	0.58	0.84	0.01	0.02	33.77	0.10	0.00	0.01	0.01	0.00	0.00	5.66	32.10
HESCO	0.00	1.66	0.69	1.90	0.10	0.00	0.00	0.05	18.09	0.02	0.14	0.03	0.00	0.00	0.00	0.08	0.00	2.04		24.79
SEPCO	0.04	0.06	2.03	0.00	2.17	0.00	0.00	0.52	3.18	0.01	0.01	0.19	0.00	0.00	0.00	6.83	0.06	5.58		20.67
TESCO	0.02	0.03	0.06	0.52	0.12	0.00	0.00	0.49	0.04	0.00	0.00	6.84	0.84	0.00	0.00	0.00	9.51	0.42	2.03	16.88
Baluch1	0.00	11.43	0.88	0.62	0.00	0.00	0.00	0.02	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.29		13.29
AJ&K	10.49	0.58	0.21	0.83	0.05	0.00	0.00	0.06	0.67	0.03	0.13	0.22	0.20	0.00	0.01	0.05	0.00	0.01	2.78	10.76
Baluch2	0.00	0.85	7.07	0.10	0.00	0.00	0.00	0.01	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.41		8.51
Gilgit	0.00	0.46	0.26	1.55	0.10	0.00	0.00	9.28	0.16	0.00	0.00	0.04	0.13	0.00	0.01	0.00	0.00	0.00	5.75	6.25
Baluch4	0.00	0.59	0.06	0.14	5.97	0.00	0.00	0.02	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	1.06	5.95
Baluch3	0.00	0.14	0.00	3.74	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.13		4.03

HW_Supply_Case and HG_Demand_Scenario at the HPC

Demand Side (TWh)	Supply Side (TWh): AJ&K	Baluch1	Baluch2	Baluch3	Baluch4	FESCO	GEPCO	Gilgit	HESCO	IESCO	KESC	KP1	KP2	LESCO	MEPCO	SEPCO	TESCO	SS	Daily Storage Use	Total
LESCO	1.61	0.00	0.09	4.77	0.34	0.60	0.01	20.10	0.72	0.49	0.00	19.93	0.02	39.90	0.75	0.00	0.01	12.40		101.75
MEPCO	0.40	4.28	1.42	13.15	0.19	0.03	0.00	4.30	0.71	0.01	0.00	2.46	0.00	0.03	29.86	0.00	0.31	14.78		71.94
KESC	0.01	5.69	2.12	4.01	0.67	0.00	0.00	0.11	11.62	0.04	34.16	0.05	0.00	0.00	0.14	0.14	0.06	3.32		62.12
FESCO	0.15	0.13	0.12	1.76	0.08	40.60	0.00	2.53	0.03	3.28	0.01	1.21	0.01	0.12	0.00	0.00	1.44	6.20		57.67
IESCO	0.00	0.02	0.03	0.13	0.01	0.00	0.00	2.22	0.06	24.35	0.02	23.54	0.08	0.01	0.00	0.00	0.00	0.00	1.33	49.15
GEPCO	13.87	0.00	0.00	0.38	0.08	0.00	14.90	1.56	0.01	1.36	0.00	10.45	0.00	0.03	0.00	0.00	0.02	0.34		43.00
KP2	0.00	0.00	0.00	0.13	0.03	0.00	0.00	18.08	0.00	0.00	0.00	0.13	23.43	0.00	0.00	0.00	1.03	0.17		43.00
KP1	0.00	0.17	0.10	0.88	0.10	0.00	0.00	0.17	0.32	2.01	0.10	43.56	0.15	0.12	0.24	0.08	0.08	0.00	16.46	31.61
HESCO	0.00	0.93	0.50	1.66	0.24	0.00	0.00	0.03	19.28	0.02	0.06	0.02	0.00	0.00	0.02	0.22	0.01	1.82		24.81
SEPCO	0.02	0.02	1.26	0.00	2.71	0.00	0.00	0.50	2.22	0.00	0.00	0.20	0.00	0.00	0.04	9.38	0.11	4.22		20.69
TESCO	0.00	0.01	0.01	0.15	0.06	0.00	0.00	0.16	0.01	0.01	0.01	4.91	0.59	0.00	0.01	0.00	14.93	0.00	4.41	16.47
Baluch1	0.00	11.48	0.85	0.60	0.01	0.00	0.00	0.03	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.27		13.30
AJ&K	12.45	0.11	0.04	0.31	0.01	0.00	0.08	0.01	0.05	0.48	0.06	0.02	0.08	0.19	0.14	0.06	0.00	0.00	3.62	10.47
Baluch2	0.00	0.79	7.15	0.10	0.17	0.00	0.00	0.01	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22		8.50
Baluch4	0.00	0.69	0.33	0.12	8.02	0.00	0.00	0.01	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.36	5.89
Gilgit	0.00	0.31	0.13	0.92	0.04	0.00	0.00	16.72	0.07	1.25	0.01	0.69	0.75	0.07	0.05	0.01	0.01	0.00	15.28	5.76
Baluch3	0.00	0.14	0.00	3.74	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.12		4.03

Appendix-I: Details of the Transmission System Findings

OG_Demand_Scenario													
Segment	Lenghth (Km)	LW_Supply_Case at LPC			LW_Supply_Case at HPC			HW_Supply_Case at LPC			HW_Supply_Case at HPC		
		Max. Flow (GW)	Voltage (kV)	No. Of Lines	Max. Flow (GW)	Voltage (kV)	No. Of Lines	Max. Flow (GW)	Voltage (kV)	No. Of Lines	Max. Flow (GW)	Voltage (kV)	No. Of Lines
Segment1	134	14.14	1000	5	14.31	1000	8	12.07	1000	5	12.07	1000	4
Segment10	120	35.32	1000	19	28.82	1000	15	34.79	1000	19	34.79	1000	16
Segment11	150	31.29	1000	18	21.49	1000	12	27.34	1000	16	27.34	1000	13
Segment12	96	13.78	1000	5	5.11	500	5	12.65	1000	4	12.65	765	5
Segment13	181	4.89	765	3	4.89	765	3	2.15	500	3	2.15	220	3
Segment14	90	13.78	1000	5	5.11	500	5	12.65	1000	4	12.65	765	5
Segment15	98	9.68	765	5	10.01	765	5	10.59	1000	4	10.59	1000	4
Segment16	252	11.26	1000	8	5.37	765	4	18.19	1000	14	18.19	1000	9
Segment17	330	0.51	220	4	5.15	765	5	5.95	1000	4	5.95	500	4
Segment18	432	4.06	765	4	2.57	765	3	4.27	765	5	4.27	765	3
Segment19	307	10.57	1000	9	6.38	1000	4	14.97	1000	13	14.97	1000	8
Segment2	142	23.00	1000	13	22.24	1000	13	25.17	1000	14	25.17	1000	13
Segment20	343	1.24	500	2	1.50	500	3	1.41	500	3	1.41	500	3
Segment21	450	1.46	500	3	12.37	1000	13	7.22	1000	5	7.22	765	3
Segment22	230	1.99	500	3	0.39	220	2	2.19	500	3	2.19	500	2
Segment23	86	8.81	765	5	7.63	765	4	9.53	765	5	9.53	765	4
Segment24	115	8.34	765	5	8.34	765	5	8.50	765	5	8.50	765	5
Segment25	218	5.70	765	4	3.85	765	3	10.86	1000	5	10.86	765	4
Segment26	61	8.34	765	4	8.34	765	4	8.50	765	4	8.50	765	4
Segment27	91	0.70	220	3	2.00	500	2	0.50	220	2	0.50	500	2
Segment3	204	2.50	500	4	2.95	500	4	2.62	500	4	2.62	500	4
Segment4	115	20.26	1000	11	19.28	1000	10	21.22	1000	11	21.22	1000	11
Segment5	126	33.80	1000	18	29.50	1000	16	34.54	1000	19	34.54	1000	17
Segment6	202	7.80	765	5	7.47	765	5	6.78	765	5	6.78	765	5
Segment7	91	1.87	500	2	4.00	500	4	1.95	500	2	1.95	132	1
Segment8	124	1.00	220	5	24.85	500	3	0.74	220	3	0.74	500	3
Segment9	130	2.78	500	3	4000.00	500	5	5.43	765	3	5.43	132	4

HG_Demand_Scenario													
Segment		LW_Supply_Case at LPC			LW_Supply_Case at HPC			HW_Supply_Case at LPC			HW_Supply_Case at HPC		
	Lenghth (Km)	Max. Flow (GW)	Voltage (kV)	No. Of Lines	Max. Flow (GW)	Voltage (kV)	No. Of Lines	Max. Flow (GW)	Voltage (kV)	No. Of Lines	Max. Flow (GW)	Voltage (kV)	No. Of Lines
Segment1	134	19.29	1000	11	19.71	1000	11	17.85	1000	10	19.66	1000	11
Segment10	120	37.03	1000	20	33.28	1000	18	38.23	1000	20	37.05	1000	20
Segment11	150	31.94	1000	18	26.14	1000	15	32.86	1000	19	29.51	1000	17
Segment12	96	10.95	1000	4	6.01	765	3	12.95	1000	5	8.15	765	4
Segment13	181	0.94	220	5	5.24	765	3	2.88	500	4	6.98	765	5
Segment14	90	10.95	1000	4	6.01	765	3	12.95	1000	4	8.15	765	4
Segment15	98	11.99	1000	4	8.72	765	5	12.58	1000	4	13.24	1000	5
Segment16	252	9.51	1000	5	3.58	765	3	18.94	1000	14	11.61	1000	9
Segment17	330	6.85	1000	4	7.48	1000	5	5.89	1000	4	9.20	1000	8
Segment18	432	3.74	765	4	2.86	765	3	5.62	1000	4	3.69	765	4
Segment19	307	9.98	1000	8	6.75	1000	4	16.59	1000	14	12.50	1000	11
Segment2	142	24.14	1000	14	24.65	1000	14	27.86	1000	16	26.99	1000	15
Segment20	343	1.54	500	3	2.45	500	5	1.97	500	4	2.98	765	3
Segment21	450	1.35	500	3	16.16	1000	17	8.74	1000	9	25.54	1000	27
Segment22	230	2.73	500	4	13.00	1000	9	1.64	500	2	14.12	1000	10
Segment23	86	9.28	765	5	8.83	765	5	11.71	1000	4	9.66	765	5
Segment24	115	10.47	1000	4	10.38	1000	4	10.80	1000	4	10.80	1000	4
Segment25	218	7.65	1000	4	4.11	765	3	10.64	1000	5	7.00	765	5
Segment26	61	10.47	765	5	10.38	765	5	10.80	765	5	10.80	765	5
Segment27	91	1.58	500	2	2.42	500	3	1.56	500	2	3.87	500	4
Segment3	204	3.81	500	5	4.22	765	3	3.45	500	5	3.51	500	5
Segment4	115	21.33	1000	11	24.59	1000	13	24.19	1000	13	24.32	1000	13
Segment5	126	30.85	1000	17	33.71	1000	18	34.49	1000	19	41.54	1000	22
Segment6	202	9.88	1000	5	7.77	765	5	9.88	1000	5	7.17	765	5
Segment7	91	0.18	132	2	6.00	765	3	3.45	500	4	4.50	500	5
Segment8	124	2.33	500	3	3.00	500	3	2.34	500	3	3.96	500	5
Segment9	130	0.22	132	3	6.00	765	3	0.36	132	5	5.64	765	3

Appendix-J: MESSAGE Input Parameters Assessment

Data and Assumption:

Variable costs (US cents/kWh) - (DIW, 2013)

Hydro	Wind	PV	PHES	Biomass
0.006	0.0174	0.021	0.006	0.02

Fixed Costs (US $/kW/Yr.) (IRENA, 2013)

Hydro*	Wind	PV	PHES	Biomass
10.5	26.25	18.75	15	75

Life (Years) Assumption

Hydro	Wind	PV	Storage	Biomass
50	25	20	50	30

Construction period (Years) Assumption

Hydro	Wind	PV	Storage	Biomass
5	2	2	5	3

Installed Capacity (kW)

		HPP	Wind	PV	Daily Storage	Biomass	Seasonal (Hydro)	Total (kW)
OG_Demand_Scenario	LW_LW_Supply_Case	54500000	45800000	55057135	4400000	16000000	12000000	187757135
	LW_HW_Supply_Case	54500000	45800000	161700000	7900000	14000000	12000000	295900000
	HW_LW_Supply_Case	54500000	91700000	7320000	4400000	16000000	12000000	185920000
	HW_HW_Supply_Case	54500000	91700000	85438259	7900000	12000000	12000000	263538259
HG_Demand_Scenario	LW_LW_Supply_Case	54500000	45800000	94900000	7800000	22000000	22000000	247000000
	LW_HW_Supply_Case	54500000	45800000	220000000	14040000	21000000	20000000	375340000
	HW_LW_Supply_Case	54500000	91700000	61293648	7800000	20000000	19000000	254293648
	HW_HW_Supply_Case	54500000	91700000	198900000	14040000	18000000	16000000	393140000

Weighted Parameters

Supply Scenario		Weighted Variable Cost (US$ /kWYr)	Weighted Fixed O & M Cost (US$/kW/Yr.)	2012 Weighted Invest Cost ($/kW)	Weighted Cap. Factor	Weighted Life (Years)	Weighted Const. Period (Years)
OG_Demand_Scenario	LW_LW_Supply_Case	1.15	22.97	2341.05	0.26	33.40	3.22
	LW_HW_Supply_Case	1.31	18.03	1951.19	0.17	28.79	2.80
	HW_LW_Supply_Case	1.12	25.13	2456.61	0.26	34.77	3.23
	HW_HW_Supply_Case	1.24	19.90	2095.31	0.19	30.66	2.89
HG_Demand_Scenario	LW_LW_Supply_Case	1.25	21.79	2203.47	0.26	32.06	3.11
	LW_HW_Supply_Case	1.35	17.81	1892.88	0.17	28.25	2.76
	HW_LW_Supply_Case	1.22	22.40	2222.22	0.25	32.18	3.04
	HW_HW_Supply_Case	1.36	17.90	1885.60	0.16	28.08	2.69

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