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Small-Hydroplants-Based Renewable Power Systems for Remote Regions

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DISSERTATION

by

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aus Biratnagar, Nepal

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Last but not least this work is dedicated to the two billions of rural people who are still deprived of electricity. I hope that with this work, in the course of its further improvement; will be valuable to my fellow engineers to ease decision-making process and for promoting rural electrification in a sustainable manner.

Karlsruhe, July 2004 Ramesh Kumar Maskey

Abstract

Energy was, is and will remain the basic foundation responsible for stability of economic development of any nation. It is both the source of conflict and prosperity. The conventional energy resources like Coal, Oil, Gas etc., are not only limited on earth but its use also negatively affects the environment. The energy problem is, thus, synonymous to ecological and economic problems. The vital issues for satisfying the energy demand in a sustainable manner are discussed. The urgent need to investigate the wider applicability of alternative renewable energy technologies for remote regions of developing countries is explored. The problems associated with utilizing these technologies including small hydropower in stand-alone operation are explained and a concept for overcoming these problems is discussed.

Small hydropower plants integrated with other renewable energy technologies (RETs) make the power system for remote regions more efficient and cost-effective by eliminating some of disadvantages inherent these technologies. However, an optimal mix of these technologies is a complex problem of decision-making process. A comprehensive literature survey on a number of similar researches in this field has revealed that there is a gap in planning combined operation of small hydropower plants with RETs in an isolated grid. This dissertation investigates the performance of a small hydropower plants-based decentralized renewable power system for rural electrification and deals with the development of a computer supported planning tool.

Due to low power density, unpredictable site conditions and up-front cost, RETs are not popular in developing countries. Decades of experiences in implementing small hydropower technology elsewhere suggest that rural electrification would widely be disseminated only if the energy technologies provide grid-quality and cost-effective energy to the rural population. The single-source RETs and the stand-alone small hydropower plants, located within similar hydro-meteorological conditions, may not be able to guarantee power supply throughout the year. The energy from RETs without storage devices is not suitable for reliable power scheduling. On the other hand, the capacity of a run-of-the river hydropower plant approaches its economic upper limit above which the cost per unit energy will be greater than the cost per energy from RETs with storage devices.

To address these issues, it is desirable, where appropriate, that the consumer’s power and energy demand is satisfied through a combination of power generators having different capacities. In this way, they allow flexibility in dispatching the system load optimally with regard to reliability and cost. In combined operation, the system achieves a good compromise between technical, ecological and economic efficiencies.

Furthermore, it would be uneconomical to be interconnected many stand-alone hydropower plants in remote regions of developing countries with the central power-grid in foreseeable future. Therefore, a better strategy for step-wise rural electrification would be to build several mini-grids at village and district grid levels. These will then be fed by clusters of stand-alone hydropower plants and gradually made compatible for the regional level. The rapid investment in rural electrification is also decelerated by the absence of site-specific data and appropriate tools for their quick and reliable analysis.

Abstract

To design an integrated power system characterized by non-linear and stochastic variables and constraints, a large amount of combinatorial processes must be simulated and optimised simultaneously. A computer-supported mechanism has been thus innovated, which may expedite the decision-making process for the planning of a decentralized power system from a set of easily available data input. Hence, the objectives of this dissertation are two folds: a) to demonstrate that the integration of small hydropower plants with RETs in an isolated mini-grid can achieve optimum system efficiency and higher operational flexibility, and b) to demonstrate the analytical capacity of the developed model.

This dissertation deals with the basic concept of the developed model and some preliminary analytical results obtained by investigating the technical and economic performances of a hypothetical isolated mini-grid in a remote region of Nepal.

It has been found that a small-hydro-based decentralized renewable power system improves the system efficiency with a reasonably affordable cost. These results also suggest that the model is capable for quick assessment of such an integrated system based on only few input data sets allowing a meaningful decision making. Furthermore, this model also allows engineers and technicians to perform several experiments in order to update their insights in power systems. With some further modification, this model may also be applicable in other countries in places, where similar boundary conditions prevail as those presumed in this dissertation.

Key words: Small hydropower, decentralized power system, rural electrification, mini-grid, renewable energy technology.

Kurzfassung

Die Energie war schon immer einer der Grundpfeiler der Stabilität der wirtschaftlichen Entwicklung eines jeden Landes, sie ist es noch und wird es auch in Zukunft bleiben. Aber die herkömmlichen Energiequellen, wie Kohle, Öl, Gas etc., sind auf der Erde nicht nur beschränkt, ihre Nutzung belastet auch die Umwelt. Daher ist das Energieproblem auch mit ökologischen und wirtschaftlichen Problemen gleichzusetzen. Es wird über die entscheidenden Themen, wie man den Energiebedarf nachhaltig und umweltfreundlich decken kann, diskutiert. Auch die Notwendigkeit die breite Anwendbarkeit alternativer Technologien zur Nutzung erneuerbarer Energien in abgelegenen Regionen in Entwicklungsländern zu erforschen, wird verdeutlicht. Die Probleme, die beim Einsatz dieser Technologien einschließlich der Kleinwasserkraftanlagen im Einzelbetrieb auftreten, werden erklärt und ein Konzept zur Lösung dieser Probleme erörtert.

Eine Vernetzung der Kleinwasserkrafttechnologie mit anderen Technologien erneuerbarer Energie (RETs) das Stromnetz für abgelegene Regionen effizienter und kosteneffektiver macht, indem sie einige der Nachteile, die den einzelnen Technologien anhaften, beseitigt. Die optimale Kombination dieser Technologien ist jedoch ein komplexes Problem der Entscheidungsfindung. Ein umfassendes Studium der Fachliteratur über eine Anzahl ähnlicher Forschungsarbeiten auf diesem Gebiet hat gezeigt, dass immer noch Lücken bei der Planung des Verbundbetriebs dieser Technologien in einem eigenständigen Netz bestehen. In dieser Dissertation wird die Leistungsfähigkeit von auf Kleinwasserkraftwerken basierendes Dezentrales regeneratives Energiesysteme bei der ländlichen Elektrifizierung untersucht. Sie beschäftigt sich auch mit der Entwicklung eines computergestützten Planungswerkzeuges.

Wegen ihrer geringen Leistungsdichte, unvorhersehbarer Standortbedingungen und hoher Investitionskosten sind RET-Systeme in Entwicklungsländern nicht sehr verbreitet. Jahrzehntelange Erfahrung in der Kleinwasserkrafttechnologie an anderen Standorten legt es nahe, dass die ländliche Elektrifizierung sich nur dann weit verbreiten kann, wenn die Energietechnologie der ländlichen Bevölkerung eine hohe Netzqualität bei kosteneffektiver Energie anbietet. Die Einzelenergie-RET-Systeme und die einzeln betriebenen Mikrowasserkraftwerke an Standorten mit ähnlichen hydrometeorologischen Bedingungen wären wohl kaum in der Lage, die über das Jahr verteilte Energieversorgung zu gewährleisten. Die Energie von RET-Systemen ohne Speicheranlagen ist typischerweise nicht für die zuverlässige Planung und dynamische Verteilung der Energie geeignet. Andererseits erreicht ein Flusskraftwerk eine wirtschaftliche Obergrenze, über der die Produktionskosten höher sein wird als die von RET-Systemen mit Speichermöglichkeit.

Es wäre also wünschenswert, wo angebracht, den Leistungs- und Energiebedarf des Verbrauchers durch eine Kombination von Stromgeneratoren mit unterschiedlicher Kapazität zu decken. Auf diese Art wird eine hohe Flexibilität bei der optimalen Verteilung der Netzlast unter Berücksichtigung der Zuverlässigkeit und der Kosten ermöglicht. Beim Verbundbetrieb erreicht solch ein System einen guten Kompromiss zwischen technischer, ökologischer und wirtschaftlicher Effizienz.

Kurzfassung

Ferner, für viele dieser einzeln betriebenen Kleinwasserkraftwerke in abgelegenen Regionen von Entwicklungsländern wäre es in naher Zukunft unwirtschaftlich, mit dem zentralen, landesweiten Stromnetz verbunden zu werden. Daher wäre es eine bessere Strategie für eine schrittweise ländliche Elektrifizierung, zuerst mehrere Mininetze auf Dorf- und Kreisniveau zu realisieren. Diese würden dann aus Clustern von Kleinwasserkraftwerken erzeugt und man könnte sie so allmählich mit dem Regionalnetz kompatibel machen.

Die zügige Investition in die ländliche Elektrifizierung wird auch durch das Fehlen standortspezifischer Daten und die passenden Werkzeuge für deren schnelle und zuverlässige Auswertung behindert. Um ein Miniverbundnetz zu entwickeln, das durch nicht-lineare und stochastische Variablen und Randbedingungen charakterisiert wird, ist die parallele Simulation und Optimierung einer großen Menge an kombinatorischen Prozessen notwendig. Es wurde also ein computergestützter Mechanismus als Neuerung eingeführt, der den Entscheidungsfindungsprozess bei der Planung eines dezentralen Stromversorgungssystems auf der Grundlage einer einfach erhältlichen Datenbasis beschleunigt. Daher hat diese Forschungsarbeit zwei Hauptaspekte: a) zu zeigen, dass bei dem Verbund von Kleinwasserkraftwerken mit RET-Systemen in einem unabhängigen Mini-Stromnetz ein Optimum an Systemeffizienz und erhöhte Betriebsflexibilität erreicht werden kann und b) die Einsatzfähigkeit des entwickelten Modells zu zeigen.

Diese Dissertation beschäftigt sich mit dem grundlegenden Konzept des entwickelten Modells und einigen Testergebnissen, die aus der Untersuchung des technischen und wirtschaftlichen Leistungsverhaltens eines hypothetischen isolierten Mini-Netzes in einer abgelegenen Region von Nepal gewonnen wurden.

Es wurde herausgefunden, dass ein auf Kleinwasserkraft basierendes Dezentrales regeneratives Energiesysteme die Systemeffizienz bei tragbaren Kosten verbessert. Diese Resultate schlagen auch vor, daß das Modell für schnelle Einschätzung solch eines integrierten Systems fähig ist, das auf nur wenigen Eingabedateien basiert, eine sinnvolle Beschlussfassung erlaubend. Weiterhin erlaubt es Ingenieuren und Technikern, eine Vielzahl von Simulationen von Stromerzeugungssystemen durchzuführen, um den Einblick in solche Systeme zu erweitern. Dies könnte auch sehr nützlich bei der Weiterbildung praktizierender Ingenieure sein, um deren Know-how auf diesem Gebiet zu erhöhen. Mit einigen Anpassungen könnte dieses Modell auch in anderen Ländern überall dort eingesetzt werden, wo es ähnliche Randbedingungen gibt, wie sie in dieser Dissertation vorausgesetzt wurden.

Stichworte: Kleinwasserkraft, Dezentrale Energiesysteme, Elektrifizierung von Ländlicher Gebiete, Kleinelektrizitätsnetzwerk, Erneuerbare Energie

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Symbol	Dimension	Description
A	[$]	Annuity
A	[mm²]	Cross-sectional area of line conductor
A_{Cond}	[mm²]	Cross-sectional area of conductor
A_i	[–]	Anisotropy index
A_S	[m²]	Surface area of a photovoltaic cell
a	[Sm]	Line stretch conductivity (admittance)
a_{ik}	[Sm]	Conductor's admittance between i^{th}-node to k^{th}-node
B_t	[$]	Project benefit at t^{th} year in constant price
C	[$]	Investment cost
C	[–]	Scale factor
C_{Const}	$[\$ \cdot kW^{-1}]$	Specific cost for planning, laying and repair of transmission line
C_{Cond}	$[\$ \cdot km^{-1}]$	Cost of conductor per kilometre length
C_E	[$]	Equipment costs
C_P	[$]	Total project cost
C_P	[–]	Betz coefficient
C_{Tr}	$[\$ \cdot km^{-1}]$	Specific cost of transmission line
C_t	[$]	Project cost at t^{th} year in constant price
C_U	$[\$ \cdot kV^{-1} \cdot km^{-1}]$	Cost per voltage per kilometre length
D_{WT}	[m]	Wind rotor diameter
d_{gmi}	[m]	Geometrical mean of the conductor spacing
F	[$]	Future amount
f	[–]	Modulating factor
f	$[\$ \cdot kW^{-1}]$	Specific cost
f	[Hz]	Frequency of the electrical network
f_E	[–]	Energy-harvesting factor
$f_{Weibul}(v_{ave})$	[–]	Weibull frequency distribution of average wind speed
g	[–]	Coincidence factor
g	$[m \cdot s^{-2}]$	Acceleration due to gravity
g_∞	[–]	Coincidence factor for an unlimited large number of consumers
H_{HH}	[m]	Turbine hub height
H_m	[m]	Wind plant site elevation
H_{ref}	[m]	Reference height
h_{amb}	[m]	Atmospheric pressure head
h_d	[m]	Vapour pressure head

h_f	$[m]$	Design head over turbine
h_g	$[m]$	Gross head
h_l	$[m]$	Head loss
h_S	$[m]$	Turbine setting height
I	$[A]$	Line current flowing through the impedance
I	$[\$]$	Initial investment
I_{BB}	$[\$]$	Initial investment on battery bank facilities
I_E	$[-]$	Slope of energy line
$I_{DL(I)}$	$[\$]$	Initial investment on deferrable load type (I) unit
$I_{DL(II)}$	$[\$]$	Initial investment on deferrable load type (II) unit
$I_{DL(III)}$	$[\$]$	Initial investment on deferrable load type (III) unit
I_{HP}	$[\$]$	Initial investment on hydropower facilities
I_{ik}	$[A]$	Current flow from i^{th}-node to k^{th}-node ($i \neq k = 1,2,3 \ldots n$)
I_K	$[\$]$	Partial investment in K^{th}-year
I_{MG}	$[\$]$	Initial investment on mini-grid facilities
$I_{O\&M}$	$[\$]$	Investment on annual operation and maintenance
I_{PV}	$[\$]$	Initial investment on photovoltaic facilities
I_{rein}	$[\$]$	Reinvestment on system's component
I_{WP}	$[\$]$	Initial investment on wind power facilities
i	$[\%]$	Inflation rate
$i_{(t+1)}$	$[\%]$	Annual inflation rate at time t+1
J	$[-]$	Number of jets in case of impulse turbines
j	$[-]$	Number of equipment
k	$[-]$	Constant
k	$[m]$	Equivalent roughness
k	$[-]$	Shape or form factor
k	$[-]$	Number of days
k_{st}	$[m^{\frac{1}{3}} \cdot s^{-1}]$	Strickler coefficient
k_T	$[-]$	Clearness index
l_{ij}	$[km]$	Length of equivalent conductor
m	$[-]$	Side slope of a canal banks
m_C	$[-]$	Load utilization factor
m'	$[-]$	Ratio of flow extremity
$m_{P,sys}$	$[-]$	System's load factor
N	$[a]$	Life period of a plant
n	$[-]$	Number of nodes

n	[−]	Number of planning and construction phase
n	[day]	Julian day of the year
n	[min^{-1}]	Synchronous speed of a generator
n	[−]	Number of similar type of consumers
n	[a]	Investment period (beginning of payment series)
n	[−]	Number of conductors in a bundle
$n_{q,max}$	[min^{-1}]	Maximum specific speed of turbine
n_T	[min^{-1}]	Tentative speed of generator
n_P	[−]	Plant utilization factor
$n_{P,sys}$	[−]	System's plant factor
n_q	[min^{-1}]	Actual specific speed
P	[kW]	Plant capacity
$P(t)$	[kW]	Instant system load demand
P_{Pv}	[W]	Electrical power from photovoltaic cell
$P_{P,i}$	[kW]	System's power generation by i^{th}-generator
$P_{C,j}$	[kW]	System's load demand by j^{th}- consumer
P_{AG}	[kW]	Power from auxiliary generator
P_{PG}	[kW]	Power supplied by primary power generators
P_{SG}	[kW]	Power from secondary power generators
$P_{C,BL}$	[kW]	Load due to battery efficiency
$P_{C,GL}$	[kW]	Grid loss
$P_{C,IL}$	[kW]	Load due to inverters efficiency
$P_{C,ML}$	[kW]	Modified consumer's load
$P_{C,SL}$	[kW]	System's power loss
P_{Ex}	[kW]	Excess power
$P_{C,PL(II)}$	[kW]	Primary load type (II)
$P_{C,DL(I)}$	[kW]	Deferrable load type (I)
$P_{C,ave}$	[kW]	Average consumer's load
$P_{C,max}$	[kW]	Maximum consumer's load
$P_{C,min}$	[kW]	Minimum consumer's load or base load
$P_{P,ins}$	[kW]	Installed capacity of a power plant
$P_{C,r}$	[−]	Normalized load
P_{HP}	[kW]	Electrical power produced by a hydropower plant
P_{WP}	[W]	Electrical power from a wind power plant
$P_{ins,sys}$	[kW]	System's installed capacity

$P_{ave,sys}$	$[kW]$	System's average power
p	$[-]$	Number of pair poles of a generator
Q_d	$[m^3 \cdot s^{-1}]$	Design discharge through turbine
$Q(t)$	$[m^3 \cdot s^{-1}]$	Flow at duration t
Q_{max}	$[m^3 \cdot s^{-1}]$	Maximum flow
Q_{min}	$[m^3 \cdot s^{-1}]$	Minimum flow
Q_{ave}	$[m^3 \cdot s^{-1}]$	Average flow
R_b	$[-]$	Ratio of beam radiation on tilted surface to the horizontal surface
Re	$[\$]$	Rest value of a plant at the end of its technical life
R_m	$[-]$	Turbine manufacture/design coefficient
R_L	$[\Omega \cdot km^{-1}]$	Ohmic part of the line impedance
$R_{L,ik}$	$[\Omega \cdot km^{-1}]$	Ohmic part of a line impedance from i^{th}-node to k^{th}-node
r	$[\%]$	Market interest rate
$r*$	$[\%]$	Real discount rate
r	$[-]$	Reserve factor
S	$[-]$	Site-factor
S	$[W \cdot m^{-2}]$	Solar irradiance
$\bar{S}$	$[W \cdot m^{-2}]$	Average irradiance on horizontal surface
$\bar{S}_b$	$[W \cdot m^{-2}]$	Beam component of average irradiance on horizontal surface
$\bar{S}_d$	$[W \cdot m^{-2}]$	Diffused component of average irradiance on horizontal surface
$\bar{S}_o$	$[W \cdot m^{-2}]$	Average irradiance outside the earth's atmosphere
$S_{b,Til}$	$[W \cdot m^{-2}]$	Beam irradiance on tilted surface
$S_{d,Til}$	$[W \cdot m^{-2}]$	Diffused irradiance on tilted surface
$S_{G,Til}$	$[W \cdot m^{-2}]$	Global irradiance on tilted surface
$S_{r,Til}$	$[W \cdot m^{-2}]$	Albedo irradiance on tilted surface
$\bar{S}_{SC}$	$[W \cdot m^{-2}]$	Solar constant
T	$[°C]$	Water temperature
T	$[hrs]$	Hours in a year
T	$[a]$	Project's economic life
T_m	$[hrs]$	Load utilization period
T_N	$[hrs]$	Time of the period

T_n	[hrs]	Plant utilization period
t	[a]	Index representing the year under consideration
t	[a]	Time variable in an economic life
t_r	[–]	Normalized period
t_{sol}	[hrs]	True place time
t_{std}	[hrs]	Local standard time
U	[V]	Node voltage
U_N	[V]	Nominal voltage
U_1	[V]	Voltage at the beginning of the supply line
U_2	[V]	Voltage at the end of the supply line
V	[kW]	Maximum load demanded by an equipment
$\bar{v}_{HH}$	$[m \cdot s^{-1}]$	Velocity of air at hub height
v_{HH}	$[m \cdot s^{-1}]$	Wind velocity at turbine hub height
V_{max}	$[m^3]$	Maximum useful volume of a reservoir
v_{ref}	$[m \cdot s^{-1}]$	Wind velocity at reference height
v_{ave}	$[m \cdot s^{-1}]$	Average wind speed
v_{ave}	$[m \cdot s^{-1}]$	Average velocity of flowing water
W	[kWh]	Energy demand
W_C	[kWh]	Consumers energy demand
W_P	[kWh]	Energy supply by generators
$W_{C,Ex}$	[kW]	Excess energy
$W_{C,Df}$	[kWh]	Deficit energy
$W_{O,M,D}$	[kWh]	Energy needed for operation, maintenance and demolition of the plant
$W_{C,ML}$	[kWh]	Modified consumer’s demand
$W_{C,SL}$	[kWh]	System’s energy loss
X_L	$[\Omega \cdot km^{-1}]$	Reactance of inductive part of the line impedance
$X_{L,ik}$	$[\Omega \cdot km^{-1}]$	Inductive part of a line impedance from i^{th}-node to k^{th}-node
Z	[hrs]	Time correction factor
z	[m]	Surface roughness length
α	$[s \cdot hr^{-1}]$	Time dimension factor
α	[–]	Head-exponent
α_{20}	$[K^{-1}]$	Temperature coefficient at 20° C
α_{PV}	[degree]	Azimuth angle of the panels with respect to meridian
β	[–]	Power-exponent

γ_{PV}	[degree]	Tilt angle of the surface of the photovoltaic panels
γ_{PV}	$[W \cdot m^{-2}]$	Slope angle of a tilted surface with respect to horizontal surface
γ	$[Sm \cdot mm^{-2}]$	Electrical conductivity
γ_{20}	$[Sm \cdot mm^{-2}]$	Electrical conductivity at 20° C
δ	[degree]	Declination angle
ε	[–]	Constant
η	[–]	Efficiency of the cell
η_G	[–]	Efficiency of gear
η_g	[–]	Efficiency of generator
η_{Tot}	[–]	Total efficiency
η_T	[–]	Efficiency of a hydraulic turbine
η_{tr}	[–]	Efficiency of transformer and electronic equipment
η_{tr}	[–]	Efficiency of transmission line
η_t	[–]	Efficiency of wind rotor
η_{sys}	[–]	System's efficiency
θ	[°C]	Conductor's operating temperature
θ_{gen}	[degree]	Angle of incidence
θ_z	[degree]	Zenith angle
λ_o	[degree]	Reference meridian
λ	[degree]	Site meridian
μ_o	$[\Omega s \cdot m^{-1}]$	Magnetic field constant
ρ_a	$[kg \cdot m^{-3}]$	Air density at wind plant site
ρ_O	$[kg \cdot m^{-3}]$	Air density at sea level
ρ_g	[–]	Ground reflectance
ρ_W	$[kg \cdot m^{-3}]$	Density of water
σ_{Th}	[–]	Thoma's cavitation coefficient
τ_E	[–]	Energy payback factor
Φ	[W]	Radiation flow of solar light
φ	[–]	Dimensionless coefficient
φ	[degree]	Latitude
φ	[degree]	Phase angle
ψ	$[\Omega \cdot km^{-1}]$	Impedance per length
ω	[degree]	Solar hour angle
ω	$[s^{-1}]$	Angular frequency
ΔU_λ	[V]	Voltage drop at the end of the supply line
dP	[kW]	Load differential

List of Abbreviation

A	Ampere
AC	Alternating Current
ADB/N	Agricultural Development Bank of Nepal
AEPC	Alternative Energy Promotion Centre
AG	Auxiliary Generator
APS	Auxiliary Power Supply
BB	Battery Bank
BEV	Break-even Value
BPS	Battery Power Supply
C	Consumer
CADEC	Community Awareness Development Centre
CBA	Cost-Benefit Analysis
CES	Centre for Energy Studies
CF	Cost Factor
COE	Cost of Electricity
DC	Direct Current
DDC	District Development Committee
DEPSO	Decentralized Power Simulation and Optimisation
DF	Downstream Flow
DIN	Deutsche Institut für Normung eV
DL	Deferrable Loads
DM	Deutsche Mark
DRPS	Decentralized Renewable Power System
DS	Data Structure
EC	Eco-points
EF	Ecological Flow
EIR	Energy Index of Reliability
ESAP	Energy Sector Assistance Programme
EU	European Union
EUT	End-Use Technology
F	Factor of Safety
FDC	Flow-Duration Curve
FVF	Future Value Factor
FWL	Forebay Water Level
GIS	Geographic Information System
GPS	Geographic Positioning System
SHBDRPS	Small-Hydroplants-Based Decentralized Renewable Power System
HDI	Human Development Index
HHINC	Household Income
HOMER	Hybrid Optimisation Model for Electric Renewable
HP	Hydropower plant
HWL	Head Water Level
IAEA	International Atomic Energy Agency
ICIMOD	International Centre for Integrated Mountain Development
IEA	International Energy Agency

IEC	International Electro-technical Commission
IPP	Independent Power Producers
IRR	Internal Rate of Return
ISC	Initial System Configuration
ITDG/Nepal	Intermediate Technology Development Group/Nepal
IWK	Institut für Wasserwirtschaft und Kulturtechnik
JURE	Junbesi Rural Electrification
kV	Kilo Volt
kW	Kilo Watt
kWh	Kilo Watt Hour
LCA	Life-Cycle Analysis
LF	Load Factor
LO	Consumer Load Original
MARR	Marginal Attractive Rate of Return
MW	Mega Watt
NEA	Nepal Electricity Authority
NGO	Non-Government Organization
NPC	National Planning Commission
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
P	Plant, Power Producer
PF	Plant Factor
PG	Primary Generator
PI	Performance Index
PV	Photovoltaic Power Plant
PVF	Present Value Factor
REC	Rural Energy Consumers
REDP	Rural Energy Development Program
REE	Rural Energy Entrepreneurs
REPPON	Renewable Energy Perspective Plan of Nepal
RET	Renewable Energy Technologies
SCADA	Supervisory Control and Data Acquisition
SCECO	Saller-Chialsa Electric Company
SF	Site Factor
SG	Secondary Generator
SHPD	Small Hydropower Department
SIR	System Improvement Ration
SOC	State-of-Charge
TL	Transmission Line
TPT	True Place Time
TSL	Turbine Setting Height
TWL	Tail-water Level
U	Voltage
UF	Utilization Factor
UK(TH)	Universität Karlsurhe (Technische Hochschule)
U_N	Nominal Voltage

UNDP	United Nations Development Programme
UPS	Uninterrupted Power Supply
US¢	United States Cent
VDC	Village Development Committee
WP	Wind power plant
WTP	Willingness to Pay

1. INTRODUCTION

1.1 Issues of Sustainable Rural Electrification

Electricity has revolutionized the way of living in developed countries. But it is still an expensive commodity and therefore inaccessible for around 2 billions of people in the world. The rural population, especially in remote regions of developing countries, are mostly deprived of using electricity and other form of modern energy sources for the betterment of their livelihood. Through careful planning it may be possible to implement a successful rural electrification in developing countries.

However, rural electrification, in itself, is not a magic potion that can immediately heal the ill-fated rural economy of a country [Widmer and Arter, 1992]. Thus, access to electricity is a necessary but not a sufficient precondition to alleviate poverty in developing countries [IEA, 2002]. Experiences have shown that rural electrification in developing countries may trigger sustainable development if people get reliable and affordable electricity for processing their income generating activities. Rural people should be able to afford electricity at least from saving expenditure on imported energy sources such as kerosene, liquid petroleum gas, dry cell batteries etc [Barnes and Foley, 2003].

Remote regions are often blessed with natural beauties that attract tourists. In many parts of developing countries, tourism has been the main source of rural income. To sustain tourism, remote regions need unprecedented amount of energy in terms of heat, mechanical power and light. This energy demand is usually covered through firewood, agricultural waste and imported fossil fuels. These fuels are neither cheap nor pollution free. Due to remoteness and rugged topography, it is technically, economically and ecologically not viable to supply electricity based on fossil fuels and also through the extension of a national grid. As an impact, many developing countries are facing both the deforestation and the draining off of hard-earned foreign currency.

Fortunately, renewable energy sources such as hydro, solar, wind, biomass and also geothermal are indigenous resources in many remote regions of developing countries. Greater use of such resources reduces the consumption of fuel-wood and fossil fuels, decreases dependency on imported fuels, creates jobs, improves education and brings socio-economic cohesion within the microeconomic level. Moreover, it supports balance of trade, security of supply and protection of environment at macroeconomic level [EU, 1997; Allderdice and Rogers, 2000].

There is an urgent need to assess the wider applicability of renewable energy technologies for rural electrification. However, the use of such technologies in remote regions poses several challenges. Concerned governments, stakeholders and scientific communities have rigorously discussed these challenges and issues in various occasions.

Summarizing the outcome based on experiences gained elsewhere and mostly from Hindukush Himalayan regions[1], the rural electrification in remote regions may be generally categorized as a complex enterprise and mostly because of the following main problems:

- Fragile ecosystem;
- Complex social and cultural diversity;
- Struggle to satisfy basic human needs;
- Scattered load centres and low energy consumption pattern;
- Except tourist centres, electricity in rural areas is still a less priory commodity;
- Lack of technical expertise in dealing with complexity of rural electrification.

Due to low power density, unpredictable site conditions and large up-front cost, renewable energy technologies (RETs), e.g. solar and wind, are not yet very popular in many developing countries [Rijal, 1999]. Decades of experiences in operating stand-alone small and micro-hydropower technologies in these countries also suggest that the rural electrification technologies would widely be disseminated only if they provide grid-quality and cost-effective electricity to the rural population [Maskey and Nestmann, 2001]. However, lack of proper site-specific data and appropriate tools for project appraisal still make the investment in rural electrification a risky enterprise.

During the World Engineers Convention (2000), engineers and scientists have declared that proper planning and management of indigenous natural resources and the use of renewable energy technologies are vital issues for satisfying the energy demand of rural communities in a sustainable manner. An integration of all available indigenous energy sources (e.g., hydro, solar, wind, biomass, geothermal etc.) is a necessary logical developmental step to achieve economic viability and supply guarantee in remote regions of developing countries. Effective cooperation between all participating components of a power system (i.e., generation, transmission, distribution and utilization) is one of the important planning tasks for the future energy supply structure [Schmid and Bard, 2002].

Therefore the motivation was to focus into an integrated concept for rural electrification that shortens the planning, development and implementation phases. This concept has led to develop an assessment tool that supports a viable and reliable decision-making process.

This work mainly deals with the following three questions:

1. Is this integration really supports producing cost-effective electrical energy?
2. How complex is to plan, design and operate such a system in rural regions?
3. How can a rural electrification appraisal be made reliable from limited data?

[1] Hindukush Himalayan regions envelopes the following countries: Afghanistan, Pakistan, India, Nepal, Bhutan, China, Bangladesh and Myanmar.

1.2 Objectives and Scope of Work

The main objectives of this dissertation are to answer the above mentioned question in general. In particular, the objectives are two folds: to prove that the small- hydro-based decentralized renewable power systems are reliable and cost-effective and to develop a computer-supported planning tool for assessing them.

Considering the complexity of the problem, the time and financial constraints, it was not possible to test the developed tool experimentally on-site. Therefore, the ongoing discussion is primarily limited to the following scope of works. The scope of works, also build the structure of the dissertation in order to answer the above mentioned three questions:

- Literature survey and analysis of the state-of-the art technologies on combined operation of renewable power systems (Chapter 1, 2 and 3);
- Development of cost-function for system components and descriptions the developed tool (Chapter 4, 5 and 6);
- Application of the tool on hypothetical case studies (Chapter 7);
- Propose a pilot project for testing small-hydro-based decentralized renewable power systems (Chapter 8)
- Summary and vision for further work (Chapter 9).

Following subsections are devoted to describe the issues of rural electrification, concept and rationale of a small-hydropower-based decentralized renewable power system in tandem with other renewable energy technologies (RETs). Finally the chapter 1 concludes by providing research methodology and hints in to relevant chapters and appendices.

1.3 Rural Electrification Dilemma

As noted earlier, a successful rural electrification in developing countries depends on many factors. Most important among them are the economic and technical factors. Since the power demand of rural consumers is mainly due to lighting, a single-source power-generating unit may not be economical. It may be understood by analysing a typical rural electric load curve as shown in Figure 1.1.

Most remote regions in developing countries have little or no commercial and industrial activities. Therefore the power consumption pattern is not uniformly distributed over time. The day-load is relatively small whereas the evening-load is very high that lasts only for few hours a day. The load factor (refer Chapter 3) generally lies between 10-30 %.

This concentration of evening power demand requires a single-source stand-alone power plant to have maximum capacity (see dash-dot line in Figure 1.1) resulting in uneconomical utilization of the power plant.

As an intermediate solution, the **R**ural **E**lectricity **C**onsumers (RECs) in many developing countries have been mobilized to consume the daytime power by using several end-use devices. The RECs need extra investment and care for these devices for their operation and maintenance. They should put considerable efforts to use these devices during the off-peak periods. Obviously, the RECs face a double stress: financial and physical. In fact RECs desire grid-quality electricity for establishing enterprises. That eases their physical and financial stresses. However

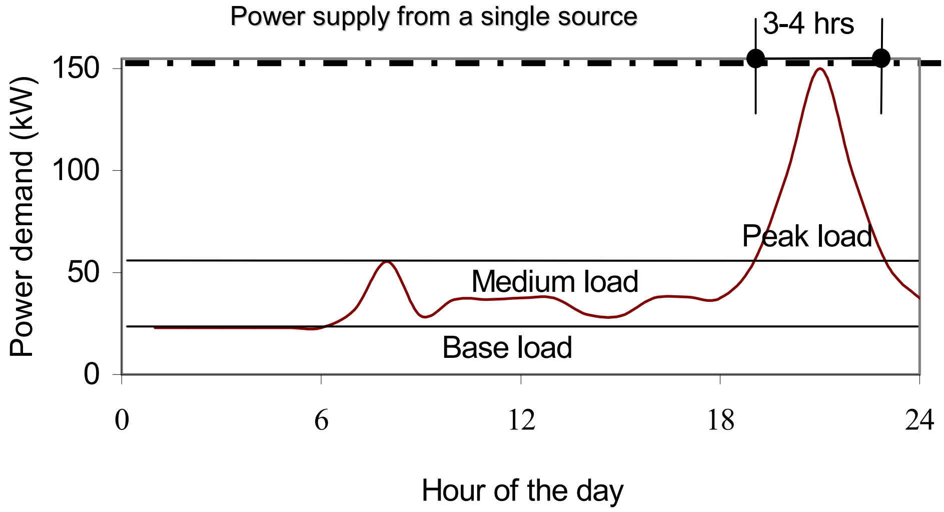

Figure 1.1: A typical rural electric load curve with power supply from a single source

stand-alone micro-hydropower plants cannot guarantee reliable electricity.

Practically, the **R**ural **E**nergy **E**ntrepreneurs (REEs) have taken no proper steps for supplying reliable and cost-effective electricity. In many instances REEs opt for establishing large scale plants without proper study on demand and supply. Eventually poorly design plants lack reliability in operation. Example in Nepal shows some RECs have installed solar or wind home systems on their own cost once the micro-hydro plants failed to supply reliable electricity. Eventually, consumers do not co-operate with REEs in case the cost of electricity is high. As a result, REEs also loose interest to continue maintaining hydropower plants. It is thus necessary to encourage REEs for increasing system's reliability at affordable cost. These facts clearly show the rural electrification dilemma.

To overcome this dilemma, it is essential to apply an integrated energy planning and management approach. This approach envisages integrating several stand-alone small hydropower plants through a mini-grid as a necessary logical step to solve both the supply and demand side problems in rural areas. This isolated grid together with the various renewable energy generating units is defined in this works as the **D**ecentralized **R**enewable **P**ower **S**ystem (DRPS).

1.4 Small Hydropower for Rural Electrification

Hydropower technology is the oldest, mature and very successful form of renewable energy technologies in the world. It remains to be the most dedicated power technology that contributes around 19 % of the world's total electrical energy supply. It is expected that this contribution will rise by 28 % in future. About 70 % of economic hydropower potential is still to be harnessed in many parts of the world and especially in the developing countries [Bartle and Taylor, 2004].

The significant problems of large hydropower development such as involuntary resettlement, interruption to river regimes and inundation of forest and landmasses due to dams and reservoirs [Goodland, 1996] may be reduced by adopting small hydropower development concept. Considering the socio-political, economic and environmental barriers to plan and execute large hydropower projects in developing countries, it has been advocated in favour of the small hydropower projects as alternative to large hydro.

The question 'how big a small hydropower plant should be' is a matter of definition that varies from country to country [Mosonyi, 1986, 1996]. There is no any general definition to classify small hydropower plants [Hildebrand, 1993]. In Germany less then 1 MW is defined for the small hydropower plant, whereas 15 MW, 25 MW and 30 MW are the maximum limits for small hydropower capacity in India, the United States of America and in China respectively. Table 1.1 presents the classification of hydropower plants based on installed capacity that has been used for the present study.

Table 1.1: Classification of small hydropower plants according to installed capacity

Type	Range	Purpose
Pico	< 10 kW	Battery charging, household use
Micro	10-100 kW	Rural stand-alone power supply
Mini	100-1000 kW	Rural isolated or regional grid
Small	100-10000 kW	Rural isolated or central grid

However, it closely reflects the definition adopted by various authors [Börner, 1982; Naidu, 1997] and based on the experience from Hindukush region [Aitken et al 1991]. As will be shown in Chapter 4, the classification of hydropower also depends on head and total project costs.

According to head, small hydropower plants may also be broadly classified as low (h_f < 15 m), medium (15 <h_f <50 m) and high-head (h_f > 50 m) depending upon power and the physical requirements of the selected site [Fritz, 1984]. According to energy-economy, small hydropower plants may also be run-of-river or storage type and may be used for the base-load, semi-peak or peak-load in an electric gird. Small hydropower plants may run in stand-alone, isolated-grid and central grid mode. Description of all types of hydropower plants is out of the scope of this study. Mosonyi, 1987 provides a complete classification of hydropower plants according to various uses.

The basic physical principles of large-scale hydropower are applicable to small-scale hydropower. However the risk associated with the construction of small-scale hydropower projects due to its physical size is relatively low than large-scale hydropower. Therefore, small-scale hydropower projects are attractive for both private entrepreneurs and the government. The basic approach in planning small hydropower projects is to search for both economically and financially best options that bring the most benefit to its developers and users. Like large hydropower engineering, small hydropower also requires a synthesis of knowledge from all branches of science and technologies. Hence the planning of small hydropower projects also poses expensive and complex tasks for engineers.

Many planning tasks are based on trial and error method involving a lot of repetitions and iterations. Manual planning of a hydropower project basically consists of a process that simulates and optimises various components separately. That leads to a definite number of options based on which an appropriate decision has to be made. Since such process is time consuming requiring various specialists right from the project formulation, it increases the cost of the project. Due to the economy of scale, many governments in developing countries did not give proper attention to develop small hydropower in the past. Consequently, many potential sites were either left unevaluated or abandoned. Recently there is again a renewed interest to develop small hydropower world-wide due to social and environmental benefit for its users.

For rapid analysis of a project, a computer-supported simulation and optimisation model is thus highly desirable. An attempt is made here to develop a computer-supported model of a general run-of-river small hydropower plant, which is suitable to process any site economically under limited data and adequate boundary conditions.

1.5 Concept of Small-Hydro-Based Decentralised Renewable Power Systems

A Decentralized Renewable Power System (DRPS) as defined above may include, where appropriate, almost all kinds of available energy technologies sharing the electrical load in proportion to their capacities.

The concept of small-hydro-based decentralized renewable power system (SHBDRPS) is that the base and intermediate loads are covered by a number of small hydropower plants in cooperation with or without other renewable energy technologies (RETs; e.g., Photovoltaic and wind) whereas the peaks are covered using energy storage devices. They may suitably include energy storage mediums such as batteries, hydrogen for fuel cells, flywheels, compressed air, pumped water storage etc., in order to increase flexibility and reliability in dispatching energy on demand. A DRPS can also be designed modular ranging from low voltage village power grid (Mini type > 1 kW) to medium voltage power grids (Medium type <1 MW). This modularity allows rural electrification strategically appropriate (Refer Chapter 5 and 8) to integrate into the existing development philosophy of any nation [Maskey et al, 2003].

It is thus desirable that energy demand could be covered through a mix of renewable power plants having different capacities so that they share the load effectively in proportion to their capacities.

To cope with the short and the long-term fluctuations in supply and demand, storage and power controlling facilities within the system must also be incorporated. Since rural electrification highly depends upon various site-specific features, it does not lead to standardize a DRPS. An optimal load sharing (see Figure 1.2) among various power plants in DRPS - the **P**erformance **I**ndex (PI) - is a function of relationships between mainly three factors: a) the site factor, b) the plant factor and c) the cost factor.

$$PI = f(SF, PF, CF)$$

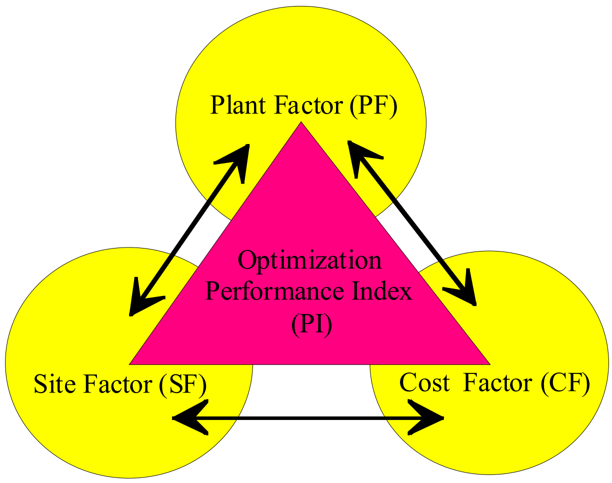

Figure 1.2: The concept of optimal load sharing

The site factor includes local geological, social and ecological parameters that should be considered for a particular project area. The plant factor is related to the type and quality of machinery to be installed and that is eventually dependent upon the local site and market conditions. The cost is major factor based on which a decision is taken. The effects of other intangible parameters are usually transformed into monetary terms and analysed using available tools.

Optimality between these factors should be achieved imposing various boundary conditions on the system. These conditions allow optimisation of both components' size and the operation control. This concept facilitates a compact system design, reduces the losses, increases the compatibility and finally encourages local manufacturers and power developers. Consequently it is possible to produce guaranteed and cost effective electricity [Hille and Dienhart, 1982]. The objective function of a power system optimisation is to achieve an optimum Performance Index, i.e., the system's efficiency that gives the lowest possible cost of energy or the highest net present value on investment.

In practice, the concept of load sharing by a number of different power plants has been applied for the economic operation of conventional large-scale central power systems. The concept of integrating small hydropower with other RETs through a Decentralized Power System in developing countries is new and challenging.

Since the operation of small hydropower plants is flexible and cheaper at base and peak demand as compared to other RETs, it allows optimisation of both component size and the operation control of the system. Moreover, developing countries have a long experience in operating stand-alone hydropower technologies. In many cases a cluster of hydropower plants can be easily found located within a radius of 5-6 km. It would be a logical step to interconnect all of these hydropower plants through a local power grid and let them share the load appropriately.

However, hydropower plants alone, located within a few kilometres and having similar hydro-meteorological conditions may not be able to guarantee power supply throughout the year. Therefore, they should be augmented either by relatively large reservoirs or by renewable technology with some storage facilities. This augmentation reduces the installed capacities of participating plants and hence it reduces the system's up-front cost [Maskey et al, 2002].

In the present work, a hydropower based power system with renewable energy technologies (wind and photovoltaic power plants) and energy storage facility (battery bank) has been modelled.

Although the economy of scale plays a role in the implementation of any project, it may be generally stated for hydropower that the higher is the plant design discharge Q_d (m³/s) or the plant power capacity P_p (or with other words, the lower the plant discharge-duration in days or percentage) the higher is the production cost of the power unit ($/kWh). Thus there can be found the maximum of Q_d respectively of P_p or the minimum value of availability of Q_d respectively P_p which can be termed as $Q_{d, limit}$, $P_{p, limit}$ and limit days or limit of duration percentage. This limit means that it is not economical to increase the Q_d or P_p (respectively diminish the duration percentage) but to supply the needed supplemental power to the network ($P_{network\ needed} - P_{p\ limit}$ of hydro) by either a solar or a wind power plant together with power storage devices or eventually a diesel.

It is, therefore, postulated here that by integrating a cluster of small hydropower plants with other renewable energy technologies into a unified power system, supply of sustainable electrical energy can be guaranteed with a net positive impact on the rural economy and the environment.

Due to innovation and improvement in manufacturing technologies, the specific cost of RETs is decreasing rapidly. Therefore, there exists a possibility to optimise the capacity of all participating energy technologies. An important advantage of hydropower plants over other RETs is that the former makes much more efficient use of the primary energy, the potential energy from sun. The overall efficiency of a hydropower plant, if designed properly, is more than 70% where as the efficiency of other RETs hardly exceeds 40% (refer Chapter 5). Other advantages are long life, low operational cost; cheap production cost and quick response to the system's load variation (refer Chapter 3).

Small hydropower technologies are robust and well accepted in mountainous regions of developing countries. An integration of several existing small-scale hydropower plants together with RETs in remote regions increase, on one hand the reliability and flexibility of system operation, on the other hand reduce the energy cost. Therefore, small hydro-based decentralized renewable power system could be a reliable and feasible preposition.

For example, in the remote and ecologically sensitive mountainous regions of Nepal it is difficult to harness their abundant hydropower potential technically, environmentally and economically sound manner. Moreover, due to rugged topography and poor load centres, supplying power through central grid or transporting fossil fuels is expensive [Banskota et al, 1990]. On the other hand, extremely low per capita energy consumption in such regions magnifies decentralized power systems because so little electricity is needed to raise the quality of life in these regions. Remote mountainous regions of Nepal are places for tourist's attraction where people are willing to pay for guaranteed electricity.

Several hundreds of micro-hydro plants ranging from 1-100 kW has been installed either stand-alone or add-on mode and operated in these regions. However, not all of these plants have the possibility to be interconnected with the powerful transmission lines [Tamrakar and Karki, 2003]. Fortunately, these locations are also blessed with renewable resources such as solar, wind and biomass. In such cases, there is a need of strategies for building a cluster of isolated grid systems all over the country first and then gradually make them compatible to the regional grid [Maskey et al, 2003]. The above-mentioned concept has been applied to a hypothetical case using data from two rural mountainous regions of Nepal. This is discussed in Chapter 7 and 8.

1.6 Rationale for Integrating other Renewable Energy Technologies

The fundamental criteria for sustainability are that all the key factors interacting within a global system should be in equilibrium. Hence for a sustainable development, there must be equilibrium between economy, ecology and society (see Figure 1.3)

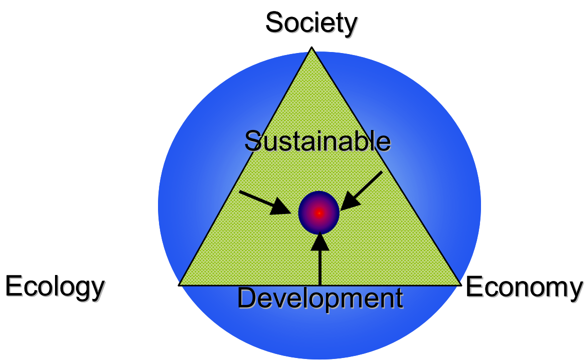

Figure 1.3: An abstract model for sustainable development

Since renewable energy - if managed properly - is the key factor in harmonizing socio-economy with ecology, a compromise should be found in achieving sustainable energy through the use of renewable energy resources. These resources are well distributed throughout the world and, in many cases; they are mutually compensatory to each other. Renewable energy technologies have been considered as alternatives to conventional energy technologies. Some of these technologies are already matured and are market competitive to replace or at least to retrofit the conventional energy technology of similar size.

Analysing the world scenario of historical energy consumption and supply pattern obtained from various studies [Rohde, 1980] a clear picture emerges that renewable energy technologies played a considerable role to cover energy demand during every epoch of energy transformations in the past. Its role is even more distinct in the foreseeable future where fossil and fissile fuel fired technologies are becoming obsolete purely due to environmental reasons [see Figure 1.4].

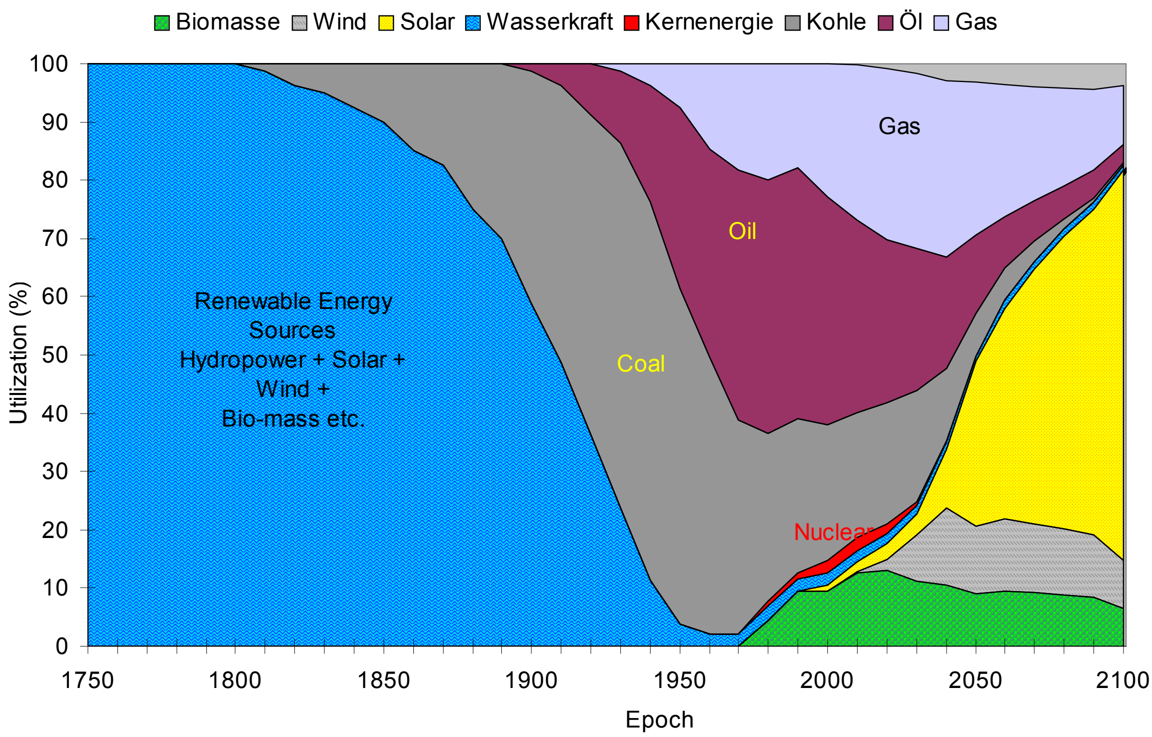

Figure 1.4: Epoch of energy resources utilization (Modified after Rohde, 1980)

This Figure also indicates the necessity for adapting concrete policies to support renewable energy technologies for sustainable energy supply in long-term. There are three main attributes to renewable energy resources:

- Free availability,
- Allowance for modular technology, and
- Emission free.

Renewable energy resources are available freely in different intensity at different periods of the year (refer Chapter 5 section 5.2).

The compensatory nature of renewable energy resources could be utilized to decrease the operation cost of the system and to increase their availability. The energy technologies based on renewable resources can be made modular ranging from few watts to some megawatt. Together with energy storage devices RETs make an integrated system possible to match supply and demand with respect to time and space. However, this will require an intelligent load-dispatch-management system, which is also known as supervisory control, to increase reliability of the system [Manwell et al, 1998]. Since most of the renewable energy resources are not “burnt” to be transformed from one energy form to another, they are emission free. In short, the renewable energy sources are environmental friendly and therefore sustainable in long run. Developing countries must open a wider access to technologies for the utilization of their indigenous renewable energy sources [Kleinkauf and Rapits, 1997].

1.7 Research Methodology

Within the scope and the limitation of work, a comprehensive research methodology was designed as shown in Figure 1.5. The research was conducted systematically studying comprehensive multidisciplinary subjects in renewable energy engineering. The objective was to identify the gaps in capacity optimisation and operation strategy in the field of small-hydro-based decentralized renewable power systems. The research methodology has been broadly divided into three main phases:

Preparatory phase: During this phase, the author was involved primarily in the various projects of the Institute of Water Resources Management and Rural Engineering at the University of Karlsruhe, Germany. Particularly, he prepared and delivered lectures, designed and supervised the construction of Pump-as-turbine test rig and hydropower plant demonstration stands. These activities and the feedback formed the sound base for the present research work. In this phase, an extensive literature review of related subject matters was done. A tentative research proposal and checklist for the data collection were prepared and agreed with supervisors. A detailed procedure and time schedule was also prepared for the fieldwork.

Field Investigation phase: The field investigations were conducted in Nepal. During the field investigation, various concerned organizations and local authorities were consulted to acquire necessary information about the research area. An experience survey of possible sites for decentralized power systems in two regions of Nepal were conducted for the case studies.

During this period, the author also actively participated in national as well as international workshops; seminars, congresses and conventions related to the utilization of water and renewable energy technologies. The author has also published research papers in various national and international scientific journals reflecting the need and strategy for the dissemination of rural electrification using renewable energy technologies.

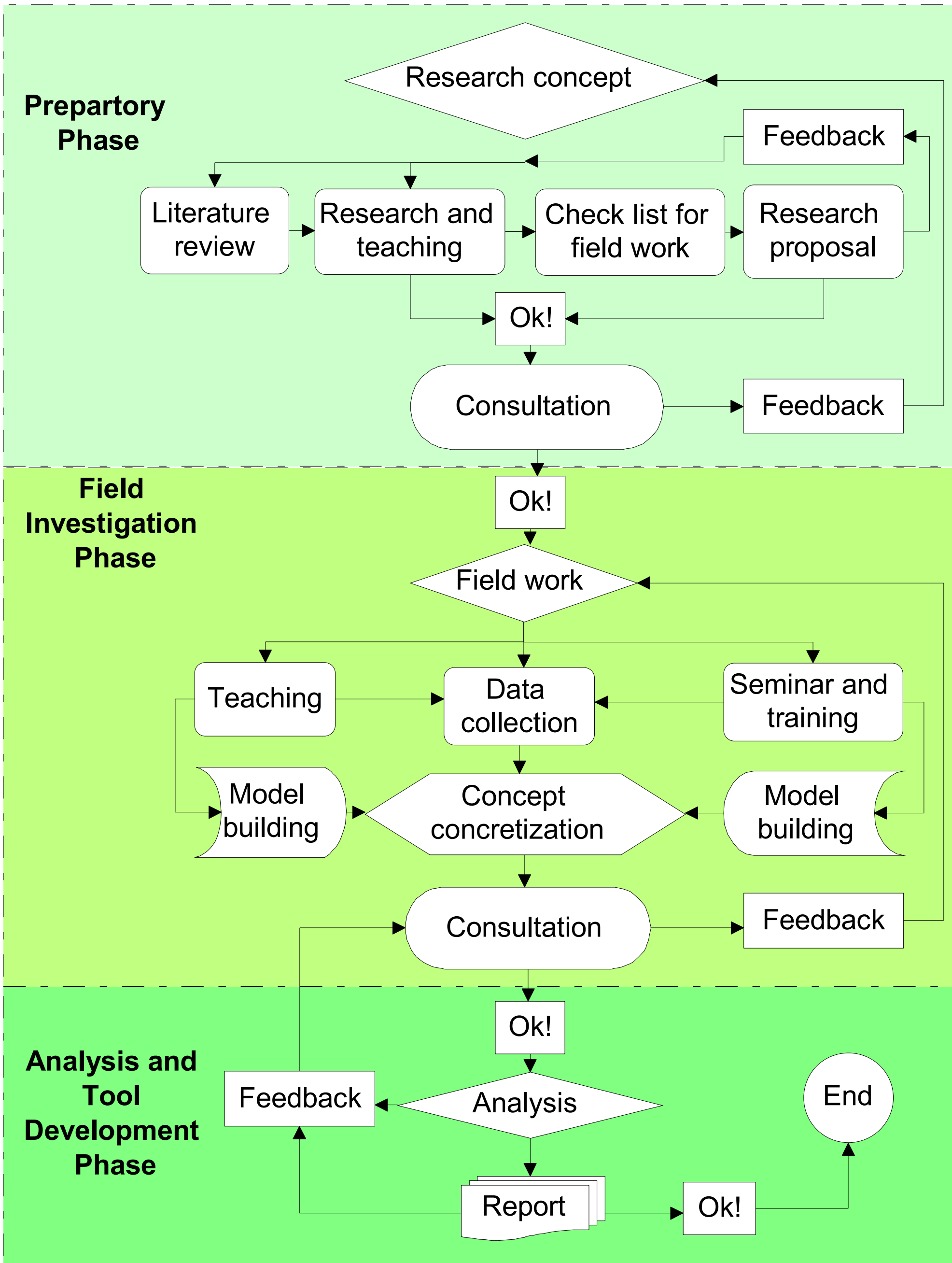

Figure 1.5: Flow chart of the research methodology

Analysis and tool development phase: The analysis of collected information is presented in Chapter 2, which gives an overview of the state-of-the art research on power system simulation and optimisation methods in chronological order. It was done to identify the research gap. The Chapters 3 reviews the energy economics applied to power systems. It defines all the terminologies and mathematical functions describing economical, technical and ecological efficiencies that provide theoretical basis for the present work. Chapter 4 is dedicated to develop and analyse the cost-functions for various components of a power system.

In Chapter 5, a detailed description of the developed tool for small-hydro-based decentralized renewable power systems is presented. Particularly, the system's components such as hydropower plant, wind plant, photovoltaic plant and mini-grid modules are discussed. Additional information required to understand the discussions on Chapters 4 and 5 is given in Appendix I. Chapter 6 presents the capacity simulation and optimisation model algorithm in detail. The concept of small-hydro-based decentralized renewable power system and the developed tool for its analysis have been applied to a case study from Nepal. Since the details of model application are presented in Appendix II, Chapter 7 presents only the results. Chapter 8 provides the prospect of the present concept for rural electrification in developing countries taking a case study of Nepal's rural electrification policy. Chapter 9 concludes the work by providing a summary of the present work and the vision for further research work. This Chapter 9 has been translated in German and presented as Chapter 10.

2 RESEARCH ON DECENTRALIZED POWER SYSTEMS

2.1 Power Demand and Supply Analysis in Retrospect

The main tasks of an engineer are to analyse problems within a physical system and to devise some methods or tools to solve these problems effectively. Michalevicz and Fogel, (2000) have noted that problems are possessions of purpose-driven decision makers. Even though the problems remain the same, the new environment due to the dynamism of the technological development confines any best solutions at present within the limited area of their application. The history has shown that the way of attacking the problem also changes accordingly.

During the end of 19th century and the mid of 20th century engineers have developed and extensively utilized graphical and analytical methods for power demand and supply analysis. Pioneering works by Rossander (1910, 1913) and Soschinski (1918) based on small power system planning are noteworthy. Because of their simplicity and demonstrativeness in solving problems, these methods have been systematically improved.

New graphical approaches for the design and operation of bigger power plants have been thoroughly discussed in the standard work of Ludin (1932, 1934). The conflicting characteristics of combined operation of hydropower with thermal power systems especially after the second world war and the huge growth in electricity demand has triggered theoretical approach in solving practical problems, such as reservoir planning, project screening and ranking, plant scheduling and optimisation of power system world wide [Mosonyi, 1948; Vogt, 1952; Brown and Hunter, 1965, Obrejkov, 1981].

As the power system engineering grew more complex both in terms of capacity and transmission boundary, conflicting decision variables for optimisation were demanded. It was essential to develop mathematical as well as numerical models for the system analysis during the last half century [Knight, 1972]. The non-linearity of the real-world system's problems and the advent of the computer accelerated further the modern heuristic process using evolutionary theory in system analysis [Michalevicz and Fogel, 2000]. As an outcome dozens of simulation and optimisation models and computer-supported tools such as the Wien Automatic System Planning Package (WASP), Supervisory Control and Data Acquisition (SCADA) to name the few most important, have been developed and used [IAEA, 1980]. These tools are applicable mostly for the large and central power supply networks.

The series of oil crisis in seventies, environmental awareness in eighties and the threat on global peace and security at the beginning this century have forced many governments in developed and developing countries to rethink on new energy policies that support rural electrification based on indigenous energy sources.

Past three decades of rural electrification were concentrated on defining the single plant locations and the optimisation of plant capacities (e.g. stand-alone small hydropower) in many developing countries such as Nepal.

Concrete and rapid decision-making to accelerate rural electrification has demanded a continuous flow of reliable information. Numerous specialized publication, conferences and seminars have witnessed the systematic development of small hydropower projects around the world. Many authors have recognized that small hydropower is one of the important components of decentralized power systems (DPS), both in developing and developed countries [Mosonyi, 1986, Dayal, 1989; Schmid et al, 2000; Nestmann, 2001; Nestmann and Maskey, 1999].

The models developed for the planning of large central power network are not suitable for small power systems used rural electrification mainly because of their complexity and lack of adaptability [Hildebrand, 1997]. Merely scaling down the large projects does not completely satisfy the specific need of rural electrification.

2.2 Literature Review on Decentralized Power Systems

A thorough literature review on available mathematical and computer-supported models for combined operation of decentralized power system using renewable resources has revealed expected results. Various authors and research institutions in recent years have carried out a large number of the state-of-the-art research in this field. With the goal to identify the gap for further research, this chapter is dedicated to discuss briefly only on those works in chronological order that are directly relevant to the present study. Indirect but relevant citations are also made appropriately as the discussion goes further.

Hildebrand (1993) proposed small hydropower and diesel power plant-based power system as relatively easy to operate and cost-effective technology. His work was based on the fact that the rural electrification in developing countries with low-load densities requires - as a rule - a low capacity energy generation and transportation system. The objective of his work was to develop an optimisation model for the planning of hydropower oriented decentralized power systems in developing countries. He used the “Branch and Bound” method for optimisation model. As a part of his dissertation, he pointed out the necessity for the integration of renewable energy technologies such as wind power in the decentralized system. However, the development of the model including such technologies was out of the scope of his work.

Ameli Taghi (1997) presented a new concept for the optimisation of power station operational planning with the consideration of the network boundary conditions. He also treated the issue whether the selected blocks are still optimal regarding the network boundary conditions. The power station scheduling with consideration of network boundary conditions was examined by coupling of a power station scheduling program with a network simulator. An optimisation program has computed the sizes, e.g. second and minute reserve power.

Seeling-Hochmuth (1998) developed an objective function whose value for a specific hybrid system design serves as a classification of merit of the design. The objective function was to combine the life-cycle costs per kWh and the penalty costs per kWh for unmet demand.

Seeling-Hochmuth applied genetic algorithms to change the decision variables. In addition, a model for hybrid systems was developed through a precise power flow description of the energy transmission in a hybrid system. Further she introduced control settings that indicate the level of battery state-of-charge and unmet demand at which either the value of the battery output or the diesel generator output had to be determined first. That reduced the number of decision variables to be optimised. The main idea behind the optimisation of the control settings instead of component sizes at each time instant was that the values for the control settings could be readily implemented in actual systems through the corresponding adjustments of system controllers. She cursorily mentioned about the possibility of inclusion of micro-hydropower technology in the hybrid system.

Mohammadabad and Riorden (2001) have focused their research on developing a computer program known as "Small hydropower advisor". The objective of this work was to ease the developers and decision makers in developing hydropower projects at preliminary stage avoiding involvement of non available experts required for the job. The advantage of this work is that it allows both hydropower experts and users to discover the appropriate hydropower sites. It includes both the technical as well as the legal information and is based on the logics of acquiring heuristic knowledge from different experts who participate in actual feasibility studies. It optimises decision variables through interface with its users, but it does not simulate and optimise various power plants at the same time. It also does not include any economic analysis.

Zelalem, (2002) indicates that a small hydropower system is non-linear both in terms of constraints and the objective function. Therefore, he suggests that the selection of an optimum small hydropower site can be found applying the non-linear optimisation techniques. As a part of his study, he examined different optimisation techniques being used in various applications till date and found that the Generalized Reduced Gradient method (GRG2) to be the appropriate optimisation techniques for the selection of optimum hydropower sites. He concludes that the method is not only capable of selecting optimum sites but also it can indicate the improvement on economic viability of the system in the course of optimisation. Zelalem's study was an extension of existing knowledge as it dealt with non-linear constraints on small hydropower systems in contrast to previous researches in this field, which were restricted to systems with linear constraints. The most relevant to the present study is his recommendation for further research on optimisation of renewable hybrid energy systems in combination with small hydropower plants for rural electrification.

Heimerl (2002) proposed a systematically complete and modular but generally accepted method for hydropower project appraisal considering the importance of hydropower for not only the economic but also the environmental and social aspects of development.

This process includes the legal, energy and general policies as well as the technical, constructional, water resources management and ecological aspects of hydropower development.

His method is hierarchical and modular and makes it possible to refine and to deepen the degree of detail according the project progress. Heimerl work is mostly concerned with the detailed estimation and economic evaluation of hydropower systems.

Stoll (2003) presents a new and highly general model for the performance optimisation of power systems. The modular approach is based on the notation used in control theory and incorporates all the principal functions of power systems (power generation, consumption, conversion, storage and power losses). According to his study complex power systems may be described, analysed and optimised in a systematic manner by defining and combining different modules. The presented method provides engineers a tool to optimise the performance of power systems using commercial power control technology. His thorough description of the system's input and output model supports the basic modelling approach taken in the present research.

2.3 Research Gap and Need for a Computer Supported Assessment Tool

Through close inspection of the stat-of-the-art research works on decentralized power system, it was noticed that the publications appeared almost every year covering a vast range of optimization problems on rural electrification. Surprisingly, however, the problem on combined operation of small hydropower with other renewable energy sources has been left unsolved. One could explain this discrepancy assuming that hydropower is more stable and relatively cheap source than solar and wind power and therefore their combined operation does not make any sense. Moreover, the general concept is that the combined operation increases the system complexity and therefore is not appropriate for rural electrification in developing countries. However for the rational utilization of indigenous resources and scientifically explain this possibility, one should take an initiation to conduct some research in this field too. The author has taken this endeavour.

Zelalem and Horlacher (2001) recommend the research need for the optimisation of hydropower in combination with other alternative energy sources. There have also been some concepts developed for integrating small-scale hybrid solar-hydroelectric power plants in existing dams [French and Miller, 1979]. The Hawaii Natural Energy Institute has established a Wind Energy Storage Test facility including pumped storage hydro at the Kahuwa Ranch in Honolulu, USA, and a small Hybrid Energy System Test facility within its campus [Neil et al in UN 1994]. National Renewable Energy Laboratory is putting a great deal of efforts for the development of computer software that simulates and optimises energy technologies including hydropower [NREL, http://www.nrel.gov/].

A number of commercially available optimisation tools using advanced algorithms based on mathematical, numerical and Evolutions strategy are available in the market [Palisade (2004), Mathworks (2004)]. Therefore, one of the major focuses in the present work is to design a simulation model that fits within the environment of existing commercial software for optimisation.

It is expedient to mention here that other computer-supported models are also available. Seeling-Hochmuth (1998) used Matlab® for power system optimisation.

Green and Manwell (1995) developed a model - HYBRID2 - for simulating combined operation of renewable energy technologies and diesel generators using Visual Basic.

HOMER (Hybrid Optimisation Model for Electric Renewable) developed by National Renewable Energy Laboratory is based on C++ [NREL, 2004]. RETScreen® International has developed a decision support tool for evaluating renewable energy technologies is based on the visual basic and Excel spreadsheet [RETScreen, 2004].

A series of research activities to develop a computer-supported model for small hydropower project analysis has been conducted using Excel spreadsheet and Visual Basic software at the University of Innsbruck [GABL, 1995, Einsiedler, 1995 and Rainer, 1998].

Recently interest is also being put forward into the development of simulation models for renewable energy technologies using Matlab based Simulink® program. This program provides a library of built-in functional block-structures for rapid prototyping of power systems and basically for visualizing power control and regulation mechanisms. Lubosny (2003) utilized Simulink for modelling operation of wind turbines. The TIWAG-Simulation model is a planning tool for the assessment of small hydropower project based on Matlab/Simulation program [Götsch et al, 2002]. However, the complexity of simulation algorithms requiring a large number of sophisticated equations, a holistic planning tool for a power system analysis is yet to be developed. It is hoped that this gap will also be filled in near future.

Many computer programs to optimise and/or simulate mixed power systems, popularly known as hybrid power systems (e.g., HYBRID2, VIPOR, HOMER, INSEL, RESSAD, SIRENE etc.), have been developed and their pros and cons have been discussed by several authors [Seeling-Hochmuth,1998, Jennings et al, 1996, Hille and Dienhart, 1992, Luther and Schumacher-Gröhn, 1991]. Many authors have utilized sophisticated computer-based evolutionary algorithms for power scheduling [Rechenberg, 1973, Goldberg, 1989, Haupt and Haupt, 1998, Michalewicz and Fogel, 2002]. But they are not readily available for engineers in developing countries. Therefore, the present simulation and optimisation process is modelled using computer-supported spreadsheet, which is simple, widely available and can be modified according to the need of the particular project objectives. These techniques are unique for specific cases but lack the possibility to assess the integration of hydropower with new RETs through decentralized power system. The model described in Chapter 6 attempts to fill this gap. Figure 2.1 shows a block diagram of the proposed model for a hydro-based decentralized renewable power system having load-dispatching ability.

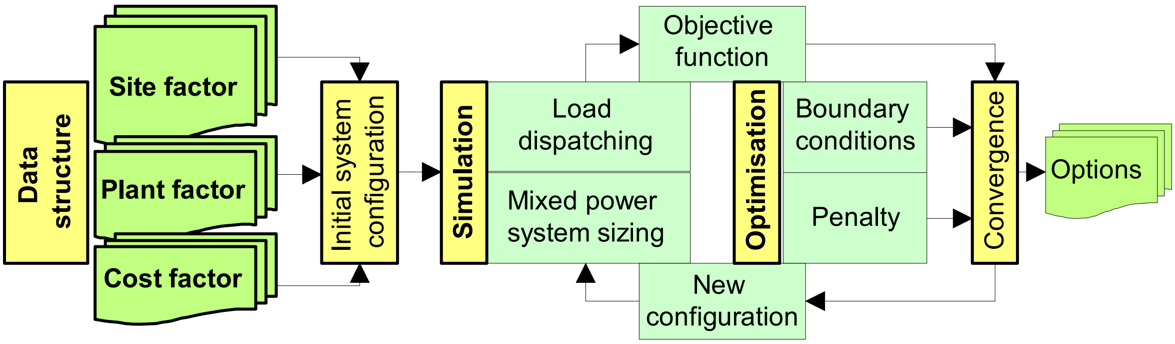

Figure 2.1: A block scheme of the simulation and optimisation process

It consists of three major stages: namely, the data structure for initial system configuration, the simulation process with mix power system sizing as well as the load dispatching and the optimisation process with the objective function and the system's boundary conditions [Maskey, 2003].energy economics for Decentralized power system

3 ENERGY ECONOMICS FOR DECENTRALIZED POWER SYSTEM

3.1 Electricity Demand Function

The planning process for a decentralized power system often requires analysis of energy supply[2] options in prospect of the electricity demand. Since there are different energy user groups during the course of time, the electricity demand[3] is the function of both the time and the consumer's behaviour. As electricity must be consumed immediately after it is generated, both the power and energy play a significant role in the project sizing, load dispatching, electricity exchanging within the interconnected grid and the tariff formulation [Müller, 1998]. The aim of this review is to give essential theoretical basis for understanding the terminologies used in the present work. The US Dollar ($) or cent (¢) has been taken as the basis for currency throughout this work.

To construct a load curve as function of time, P = f(t) (see Figure 3.1), necessary data on the characteristics of the end-users that influence the electricity demand have to be collected [Pfaffenberger, 1993]. The detail description of which is given in Appendix I).

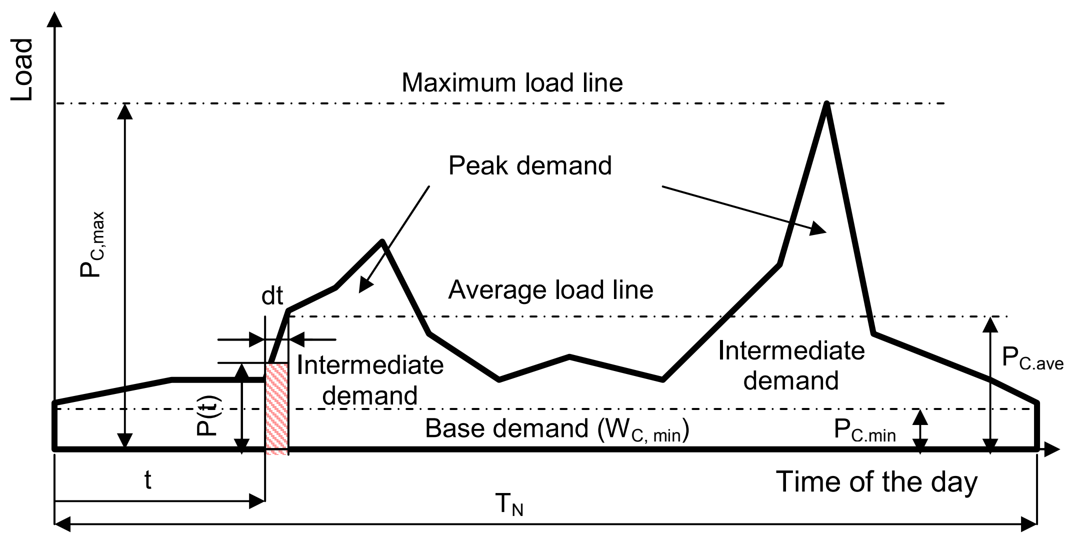

Figure 3.1: A typical electricity demand curve of a rural community

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[2] Physically, energy can never be generated, supplied, stored or lost. It can only be transformed from one form to another (The law of conservation of energy). However in energy economics a power system is considered as an industry that utilizes water, air, radiation, coal, oil etc. as 'raw materials' to produce an unique product - electrical energy. The product is then 'transported' to its consumers, where it should be consumed or stored in small magnitude. Some portion may be lost in the transportation. Thus all the economic theories and terminologies may be appropriately applied to this product.

[3] The terms 'Load' and the 'Demand' are used in this work for power and energy demanded by consumers.

The end-users in a small rural community may be electrical machines, lamps and other electrical equipment connected in the houses, cottage industries, hotels, clinics, shops, street lighting etc. The load curve establishes the input for the determination of the sizes of power system's components. Let us examine this curve with the objective to define all the essential parameters that influence the energy economics of the power system in question.

Throughout this work, indices 'P' and 'C' will be used to denote, as an example, energy supplied by the plants (W_P) and the energy demanded by the consumers (W_C) respectively. A detailed theoretical description of these curves can be found in (Ludin, 1932; Brinkmann, 1980; Müller, 1998).

Energy demand (W) of the power system is the energy that is determined as the total area under the load-demand curve. This is expressed mathematically as the integration of the load demand at any time t over a time interval of t = 0 to T_N.

$$W = \int_{t=0}^{T_N} P(t)dt \tag{3.1}$$

Where,

$P(t)$	Instant system load demand	$[kW]$
T_N	Time of the period (24 hr for a day, 8760 hr for a year)	$[hr]$

Three distinct zones can be characterized under the curve (see Figure 3.1):

Base demand ($W_{C,\,min}$) **zone** is the area defined between the minimum load line and the abscissa. It is the minimum energy demanded continuously by the system over a time period and is mathematically expressed as:

$$W_{C,min} = P_{C,min} \cdot T_N \tag{3.2}$$

Where,

$P_{C,min}$	Minimum consumer's load or base load	$[kW]$

The power plant that is scheduled to cover the base demand is known as the base-load plant.

Intermediate demand zone is the zone bordered within the average load line and the minimum load line. Since the load demand is not constant over the time period, it is difficult to calculate this energy demand mathematically. The average load ($P_{C,\,ave}$) may be determined by using the following expression:

$$P_{C,ave} = \frac{W_C}{T_N} \tag{3.3}$$

Where,

$P_{C,ave}$	Average consumer's load	$[kW]$

Peak demand zone is the zone above the average load line up to the maximum load line. The peak load is the maximum load ($P_{C,\ max}$) that can occur in the system. Depending upon the consumer's energy-use behaviour, the load curve may have one or several peak loads during the time of a day. The load is not constant over the time period and hence it is difficult to calculate this energy demand mathematically. The maximum possible energy that a power system may be connected is then expressed as

$$W_{C,max} = P_{C,max} \cdot T_N \qquad (3.4)$$

Where,

$P_{C,max}$ Maximum consumer's load $[kW]$

Not the entire installed load at the consumer's side sums up at the same time. If a single consumer is connected to the power system, then the total installed load (P_{max}) demanded by that consumer must be considered. However, if a power system supplies more than one consumer then it is important to consider not the total installed load but the way the electricity is utilized. The common mean to address that maximum consumer's load always exceeds the rated power of the plant / mini grid. Therefore a factor is introduced to take into account this coincidence.

Coincidence factor (g): considers the fact that the observed P_{max} is not always equal to the sum of the highest observed power demand by the connected equipment of a group of consumers (e.g., a community with n single consumers).

Thus,

$$g = \frac{P_{C,max}}{\sum_{C=1}^{n} P_{C,max}} < 1 \qquad (3.5)$$

Where,

$P_{C,max}$ Maximum observed load $[kW]$

$\sum_{C=1}^{n} P_{C,max}$ Sum of the highest observed load of n consumers. $[kW]$

Therefore, 'g' is always dependent on the number and characteristics of the consumers. This clearly shows that for a less number of consumers the coincidence factor quickly approaches unity. This concept is used to design current carrying capacity of conductors for transmission and distribution lines and thus plays an important role in energy economics. For a system that consists of n similar types of consumers, the coincidence factor may be estimated using the Equation A.3 given in Appendix I:

3.1.1. Load Duration Curve

In energy economics it is often enough to analyse the load with respect to duration instead of a load curve. Therefore, a time independent curve, the so-called load duration curve, is constructed by arranging the load in diminishing order with respect to duration. This gives a curve with a duration within which a load is equalled or exceeded (see Figure 3.2).

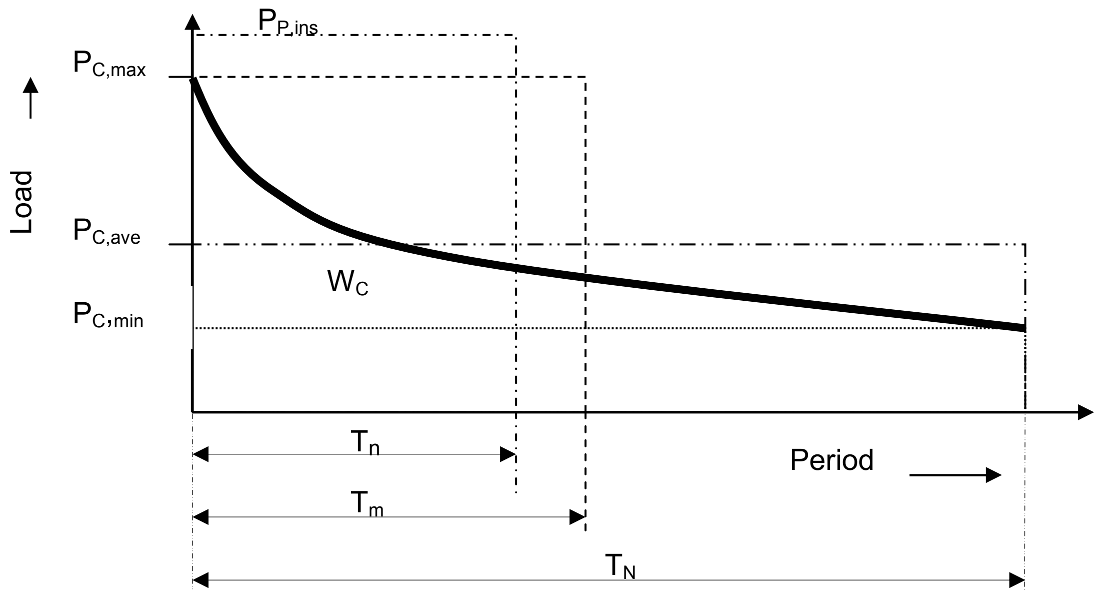


Figure 3.2: Load-duration curve and its essential parameters

The load-duration curve is an important tool for planning and generator scheduling according to its utilization period and the cost of energy production. In other words the load-duration curve provides a basic tool for the optimisation of a plant or a power system.

In connection with Figures 3.1, 3.2 and Figure A.2 in Appendix I, the following parameters should be defined in order to derive the technical as well as economic efficiency indicators of the power system in question.

Load utilization period: The load utilization period (T_m) is the duration within which the same W_C is demanded if the maximum load ($P_{C,\,max}$) is connected to the system throughout this period. Mathematically it is:

$$T_m = \frac{W_C}{P_{C,max}} \tag{3.6}$$

Load utilization factor: The ratio of W_C to $W_{C,\,max}$ is expressed as the load utilization factor (m_C) in percentage and defines what fraction of maximum energy that could be demanded by consumers has been actually utilized. It may also be expressed as the ratio of the average load to maximum load or through the ratio of load utilization period to maximum period of the utilization.

It is always less than unity.

$$m_C = \frac{W_C}{W_{C,max}} = \frac{P_{C,ave}}{P_{C,max}} = \frac{T_m}{T_N} < 1 \tag{3.7}$$

Power ratio: The relationship between minimum load to maximum load is expressed as the power ratio and is mathematically expressed as:

$$m_{C,o} = \frac{P_{C,min}}{P_{C,max}} < 1 \tag{3.8}$$

To sufficiently satisfy the consumer demand within the prescribed time period, a power plant must have sufficient installed capacity to do so. Therefore the following indicators define the power demand and supply relationships.

Plant utilization period: It is the period during which a power plant could utilize its full capacity to produce the same amount of energy that has been demanded by the consumer in the period T_N. This is expressed mathematically as:

$$T_n = \frac{W_C}{P_{P,ins}} \tag{3.9}$$

Where,

$P_{P,ins}$	Installed capacity of a power plant	$[kW]$
T_n	Plant utilization period	$[hr]$

Plant utilization factor: This shows in percentage what fraction of maximum energy that a power plant could produce has been utilized by the system. It may also be expressed as the ratio of the average load to installed capacity or through the ratio of plant utilization period to maximum period of the utilization. It is always less than unity. As the plant utilization period is less than the load utilization period, the plant utilization factor is always less than the load utilization factor.

$$n_P = \frac{W_C}{W_{P,max}} = \frac{P_{C,avr}}{P_{P,ins}} = \frac{T_n}{T_N} < 1 \tag{3.10}$$

Reserve factor: This is the ratio of the load utilization factor to plant utilization factor.

$$r = \frac{m_C}{n_P} = \frac{P_{P,ins}}{P_{C,max}} = \frac{T_m}{T_n} > 1 \tag{3.11}$$

It shows that whether a plant has enough reserve to cover all of the demand without the need of an auxiliary power supply. In a stand-alone power plant this factor tends to be larger than the plants operating in a network.

Therefore, it is one of the indicators of plant reliability. One of the advantages of combined operation is that it uses the reserves of all participating plants better than if the plants were operated individually.

As noted above the load-duration curve is geometrically derived, on one hand from the load vs. time curve, which is not readily available. On the other hand, manual construction of such curves for the analysis of a complex power system is time consuming. Further, for a system that uses power sources such as wind or solar, it is often necessary to collect a time-series (usually every 10 min. averaged interval) load demanded by electrical machines and equipment connected to that system. This is because the power supply from wind and photovoltaic plants may vary considerably within a short interval. The actual data collection procedure as described in section 3.1 is very time consuming, cost intensive and difficult to apply at the beginning of the planning phase. As a consequence the planning process is slow and expensive.

Many researchers in the past have tried to formulate the normalized load-duration curve mathematically for the rapid computational treatment of the problems in electricity economics. Rossander (1910, 1913) proposed a method to construct theoretical (normalized) load-duration curves using a simple mathematical function. Although Rossander used load curves of small electricity enterprises with mainly lighting and small motors having not so big average load factors, he concluded, with caution, that this load function could also be applied to power plants with larger load factors. Further, Soschinsky (1918) improved this method and proposed an analytical tool for projection of cost of energy, which he applied to a thermal power plant with two aggregates. Rossander's improved method has been applied in the development of the present tool. It is assumed here that the developed tool is to be used for the rural electrification in developing countries having more or less the same load factor as Rossander considered in his study. Further, it allows the use of computer. Therefore, a thorough description of this method is given here.

3.1.2 Theoretical Load Duration Curve

As per Soschinski the normalized load-duration curve proposed by Rossander could be mathematically expressed through a potential function (which is selected randomly) if the three main parameters of a load-curve, i.e., the maximum load, the average load and the minimum load are known. These parameters comprise almost all the characteristics of consumer's behaviour.

He found that the potential function (3.12) approximates quite well with the real load-duration curve.

$$P_{C,r} = 1 + \alpha t_r^{\beta} \tag{3.12}$$

Where,

$P_{C,r} = \dfrac{P(t)}{P_{C,max}}$ Normalized load [–]

$t_r = \dfrac{t}{T_N}$ Normalized period [–]

The factor α and the exponent β can be found from the boundary conditions. The detail derivation of the theoretical load-duration curve is provided in Appendix I.

The normalized load-duration equation takes the following form:

$$P_{C,r} = 1 + (m_{C,o} - 1) t_r^{\frac{m_C - m_{C,o}}{1 - m_C}} \tag{3.13}$$

Or the required power duration curve in absolute terms can be found as:

$$P_C(t) = P_{C,max}\left[1 + \left(\frac{P_{C,min} - P_{C,max}}{P_{C,max}}\right)\left(\frac{t}{T_N}\right)^{\frac{P_{C,ave} - P_{C,min}}{P_{C,max} - P_{C,ave}}}\right] \tag{3.14}$$

From the above equation it may concluded that the load duration curve can be constructed for all durations by knowing only the maximum, average and minimum values of the load.

Figure 3.3 presents an example of how a daily load duration curve changes with varying magnitude of the load utilization factor "m". Interesting to note the case when m_C = 50 % and $m_{C,o}$ = 0 the coefficients α and β are –1 and +1 respectively. From Equations 3.24 and 3.25

$$P_C(t) = P_{C,max}\left(1 - \frac{t}{T_N}\right) \tag{3.15}$$

This is, as expected, the equation of a linearly declining slope (see the bold line in Figure 3.6)

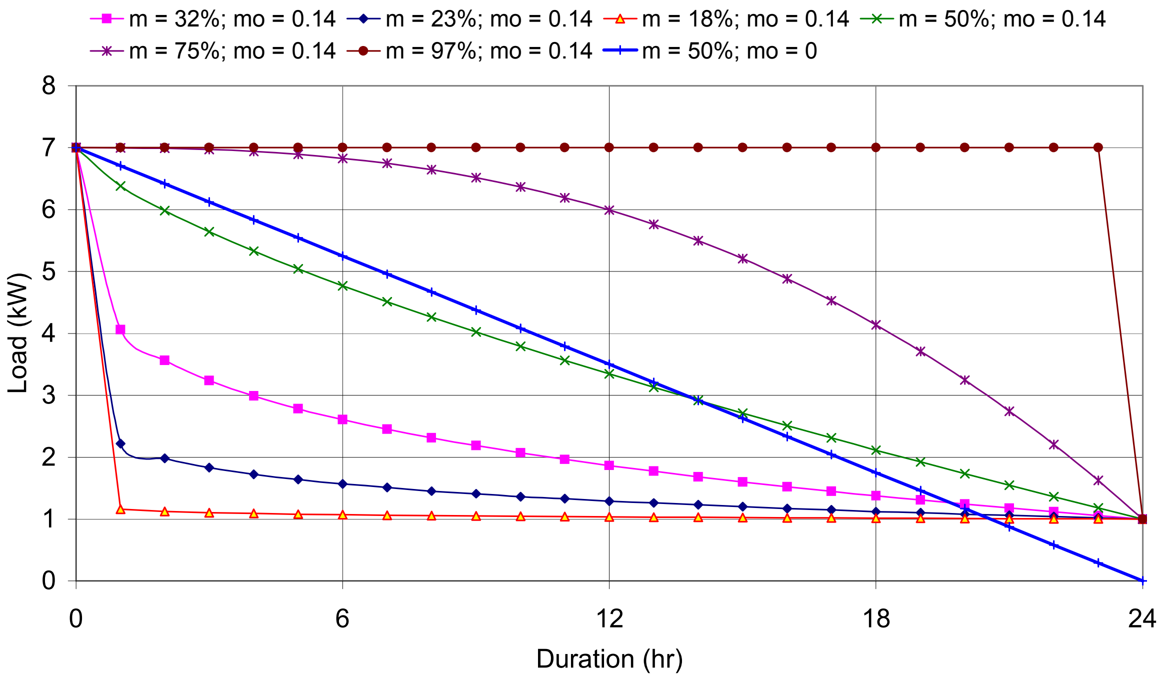


Figure 3.3: Load duration curves for different values of m

Thus, the Equation 3.15 builds up different scenarios of consumer's load on the power network by changing the value of load utilization factor (m) if the minimum and maximum values of the load are known. Where load-demand curves are not available, mostly in the case of rural electrification in remote regions of developing countries, the minimum and maximum values of load may be easily obtained or even estimated and a complete scenario of load-duration curves may be developed. It is however, not possible to reconstruct a P = f(t) curve from the load-duration curve unless the load patterns of nearest electrified villages are known.

It should be mentioned here that the theoretical duration curves might be constructed practically for all events that vary with time (e.g., discharge Q = f(t), head h_f = f(t), water level El = f(t), Water storage etc.). Mosonyi (1948) proposed a theoretical duration-curve to derive a formula for the characteristic mass-curve V = f(t) which is widely used in the design of reservoirs. Refer Appendix I for detail description.

3.2 Indicators of Technical Efficiency

The new in the proposed power system model is that it uses some parts of its own excess energy in order to supply the deficit power demand. The power and energy balance method is the key to this model. It is also envisaged to use the remaining excess energy to increase the technical as well as economic efficiencies of the power system. Hence, in the following paragraph some definitions have been introduced to highlight the technical efficiency of the power system.

Primary consumer's demand: This is the net load demand of consumers measured in kWh (refer Chapter 6). It should be covered with priority (refer section 6.1.2). In the economic analysis the benefit is estimated based on selling of this energy. The original consumer's energy demand is denoted as W_C.

Potentially saleable demand: Once the deficit energy demand is satisfied by the energy storage facilities, the remaining excess energy is used to perform some mechanical or electrical works that could be capitalized if the required facilities are planned as the project components. Since this is an additional load to the system, it could be deferred as desired. This type of load has secondary priority.

Penalty: In some cases the system cannot fully satisfy the system demand and tend to be costly if one tries to satisfy the demand completely by increasing the size of generator, turbine and transmission - or using an auxiliary power generator. The load is dispatched by deducting the portion of demand that could not be met. In such case it is said that the power system has to pay a penalty for unmet load. However, saving additional investment that would be necessary to satisfy the unmet load could compensate this loss. Such policy is not desirable in case of the requirement of highly reliable power supply. However, for a power system in rural areas it is fairly assumed as acceptable.

System demand: It is the total demand imposed to the power system that includes all added load and power losses. The area under the curve is the system's modified energy demand and is denoted by $W_{C,\ Sys}$.

Modified power supply: It is the total power supplied by the participating primary generating components together with the power supplied by a Battery Bank, other auxiliary power supply, or both of them. It is denoted by W_P.

System improvement ratio (SIR): This is the ratio of modified demand to original demand. This shows by what percentage the systems load-factor has been improved indicating the effect of the utilization of secondary energy.

$$SIR = \frac{W_{C,ML}}{W_C} \tag{3.16}$$

Where,

$W_{C,ML}$	Modified demand	[kWh]
W_C	Original demand	[kWh]

Energy index of reliability (EIR): Characterizes the probability that the power system maintains a reliable quality (given levels of frequency and voltage) and quantity of electricity supply to all of its consumers. It is the ratio of difference between the quantity of electrical energy required for the complete satisfaction of the consumer's demand and the lacking energy that for whatever reason is not sufficient for the complete satisfaction of consumer's demand to generated energy [Obrejkov, 1981].

$$EIR = \frac{W_P - W_{C,Df}}{W_P} \cdot 100\ \% \tag{3.17}$$

Where,

W_P	Total energy supply including energy from storage	[kWh]
$W_{C,Df}$	Part of energy demand that is not satisfied	[kWh]

Transmission line efficiency (η_{tr}): It is calculated as the ratio of the difference between the power demanded by the system and the transmission losses to the power demanded by the system.

$$\eta_{tr} = \frac{P_{C,ML} - P_{C,GL}}{P_{C,ML}} \cdot 100\ \% \tag{3.18}$$

Where,

$P_{C,ML}$	Modified load	[kW]
$P_{C,GL}$	Losses in transmission lines	[kW]

System load factor ($m_{P,\,sys}$): This is the factor that shows what percentage of total energy that could be produced by the system has been utilized for the complete satisfaction of the system's demand.

$$m_{P,sys} = \frac{W_P}{P_{ins,sys} \cdot T_N} = \frac{P_{ave,sys}}{P_{inst,sys}} < 1 \tag{3.19}$$

Where,

$P_{ins,sys}$	System's installed capacity	$[kW]$
$P_{ave,sys}$	System's average power	$[kW]$

System utilization factor (n_{sys}): This factor on the other hand shows what percentage of total energy that could be produced by the system has been used to satisfy the original load.

$$n_{P,sys} = \frac{W_C}{P_{ins,sys} \cdot T_N} = \frac{P_{C,ave}}{P_{ins,sys}} < 1 \tag{3.20}$$

Where,

$P_{C,ave}$	Average consumer's load	$[kW]$

System efficiency (η_{sys}): System efficiency is the ratio of net energy consumed by the system to the total energy input. In other words it is the ratio of the system utilization factor to system load factor. Mosonyi (1948) introduced this definition. Figure 3.4 shows the graphical explanation of the system efficiency.

$$\eta_{sys} = \frac{W_C}{W_P} = \frac{n_{P,sys}}{m_{P,sys}} < 1 \tag{3.21}$$

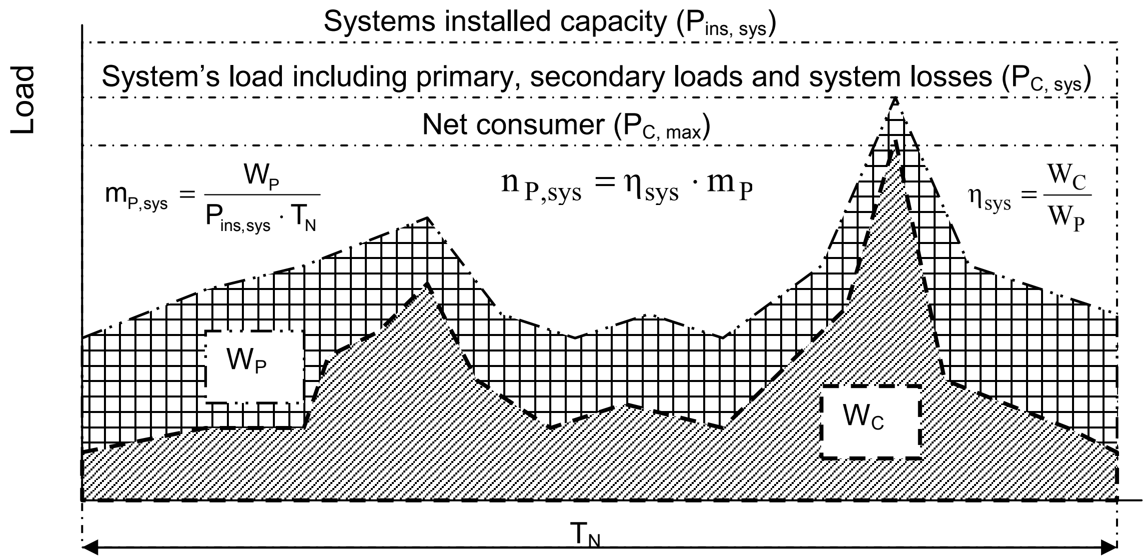


Figure 3.4: Definition sketch for system efficiency

3.3 Indicators of Ecological Efficiency

Determination of an ecological efficiency of a project in consideration is desirable for the direct optimisation process. The objective of the following description is to discuss the possibility for the inclusion of ecological indicators as one of the important parameters for decision-making. It is to be noted here that these indicators can only be deduced from statistical analysis of existing power systems. Therefore this is omitted from the present study. However, to bottom line the ecological efficiency of power technologies the following indicators are defined for future consideration:

1. The energy payback period τ_E (refer Appendix 1) is defined as the ratio of the cumulated energy needed for the manufacturing, implementation of the plant to the annual net-energy production [Kugeler und Philippen, 1990]. For small hydropower plants τ_E is 2 to 3 years (see Table 3.1).

2. The energy-harvesting factor f_E (refer Appendix 1) expresses the ratio of generated energy during the N-years of plant's lifetime to the sum of energy needed for implementation, operation and demolition of the plant [Kugeler und Philippen, 1990]. f_E for small hydropower plants ranges from 40 to 100 (see Table 3.1).

Table 3.1 presents a comparison of the ecological indicators of different energy technologies currently being used in decision-making process.

Table 3.1: Ecological indicators of different energy technologies

Type of energy technologies			Energy harvest factor[4] [-]	Energy payback period [5][Year]	Environmental cost[6] US ¢/kWh	Eco-points[7]
Hydro	Small		40 - 00	2 - 3	0.27	30
	Large	Run-off	100 - 267	1 - 2		
		Storage	100 - 205			
Wind			9 - 30	0.6 - 2	0.045	19
Photovoltaic			3 - 5	3 – 8	-	93
Coal			30 - 80	2	-	2412
Oil			10 - 30		-	1598
Gas			4 - 30		1.68 - 5.3	482
Nuclear			? - 100	1	-	40

[4] Gagnon, 2000, Heimerl, 2002.
[5] Gagnon, 2000, Heimerl, 2002
[6] Herpassen et al. 2001
[7] Herpassen et al. 2001

3. The Life-cycle analysis (LCA) method is used for the assessments of emissions and resources utilization following the establishment, production and demolition of a power plant. The two indicators discussed above are, in fact, the formula for LCA of an energy technology. Another example may be the indicator for emissions to air (e.g., the amount of CO_2 per kWh). Gagnon, (2000) presents a comprehensive example of LCA based on one hundred years of North American experience on hydropower development and its environmental impact comparison with other energy options. Based on qualitative comparison of geographical latitudes of Europe and the North America, Heimerl (2002) suggested the applicability of Gagnon's recommendations for Europe. A similar study is also necessary to conduct for the developing countries.

4. The environmental costs of a power development are defined as the extent of damages inflicted by the project after the application of mitigation measures [Herpasen et al, 2001]. It is calculated in monetary units per kWh.

5. Eco-points per kWh approach permits a comparison of the results obtained from both LCA and EC methods. If an energy technology were attributed few eco-points, then the environmental costs of a project were considered low [Herpasen et al., 2001]. However, the eco-points depend largely on the country's environmental policy and therefore it is difficult to make direct comparison between energy sources across the border.

Figures presented in Table A.2 (refer Appendix I) are obtained from various sources and thus they give only the rough impression of the ecological indicators. As may be noted the energy payback period of all energy technologies are more or less similar in magnitude. However, the energy harvest-factor is noticeably higher for hydropower than the others. This is due to the fact that the technical life of a hydropower plant and its components (weir, dam, canal, powerhouse etc.) is much higher than other forms of energy technologies. Similarly, few eco-points attributed to hydropower and wind power technologies are the clear indicators of low environmental costs.

3.4 Indicators of Economic Efficiency

Rural electrification composed of hydropower and other renewable energy technologies is an expensive enterprise in developing countries. It bears- among others- two main aims: it should support the rural economy and it should be cheap. Unlike thermal power plant, even a small-scale hydropower plants have long gestation period. The economic life goes beyond 15 to 20 years and more. In Denmark the mean life of hydropower sites is approx. 50 years. Therefore economic indicators involving time factor have the strongest arguments for or against a project.

A cost-benefit analysis (CBA) is exercised to foresee the future benefits and costs of an investment that must be merely burdened by the present generation. It is based on the philosophy of social welfare and therefore, it includes elements of socio-economic development as a whole rather than the primary concerns of financial investment and business aspects.

In the economic analysis one compares all the merits and demerits of a given project during its useful life as a whole. Figure 3.9 demonstrate a schematic sequence of an economic analysis including input, decision and output parameters.

Merits of a power system are all the tangible benefits due to selling of goods and services (i.e., power and energy) whereas the demerits are all the tangible initial costs due to manufacturing and construction and the recurring costs due to operation and maintenance during the economic life of a project. However intangible benefits (e.g., health improvement, social welfare, environmental improvement etc.) and intangible costs (e.g., cost of mitigation measures against all probable risks and damages etc.) should be included for the holistic evaluation of a project. Hence an economic analysis leads to finding an optimum project size that enhances the welfare of the general public [James and Lee, 1971].

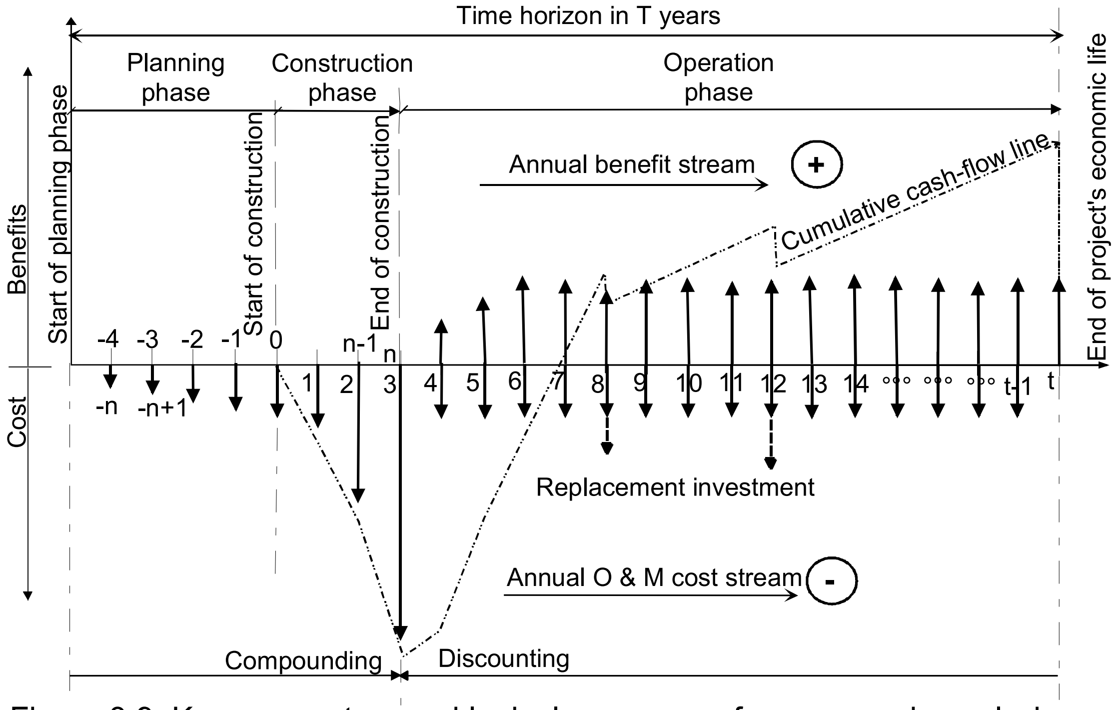


Figure 3.9: Key parameters and logical sequence of an economic analysis

Input parameters are the capital expenditure during planning and construction phases and annual expenditure during operation phase. Decision parameters are the starting point of planning and construction phase, selection of the discount rate and the project’s economic life. These parameters influence the cash-flow pattern of an investment [Buck, 1988]. As may be seen the decision has to be taken whether the compounding and discounting should be referenced to the start of construction or the end of construction phase. The positive and negative signs denotes for the benefit and cost streams of a project respectively. These streams may be either constant amount or variable. The periodic replacement investment, e.g., for electric equipment, steel construction for hydro-mechanical equipment cost must be added and discounted properly.

As an output of CBA indicators of economic efficiency, e.g., Net Present Value (Capital Value), Internal Rate of Return, Benefit-Cost Ratio etc.) are presented. The capital value can be displayed against the investigation period (from the reference date to the end of the life time). The cross-over point from negative to positive capital values indicates the year of positive net cash flow. It is also denoted as the break even point.

One of the objectives of decision-making is to compare two or more project alternatives on equal basis. An economic feasibility analysis serves this basis. To provide information on a power system following well known economic analysis methods and indicators are currently modelled in the present work:

1. Present value method
2. Annuity method
3. Benefit-cost ratio method
4. Least cost planning approach
5. Internal rate of return
6. Pay-back period
7. Profitability index

The definitions of above mentioned indicators are given in Annex I.

4 COST-FUNCTIONS FOR COMPONENTS OF A POWER SYSTEM

4.1 General

One of the difficulties in the overall simulation and optimisation of a power system is that the investment costs of system's components are not known beforehand. The investment costs are the function of project's component sizes. On the other hand, the component dimensions are the function of various site-specific factors (weather, geology, hydrology, socio-economy, policy etc.) to mention few of them. Obviously the cost-functions are highly non-linear. Since a computer supported optimisation process needs continuous iteration of component's sizes, it is desirable to use a cost-function that can - in order of magnitude - approximate the investment costs of the project in question. Two forms of cost-functions for rough estimation have been frequently used in practice. The first one is based on specific cost ($/kW) and the other one is found empirically based on either only power (kW) or power and head (m) together. For the present work cost functions for different power components are discussed.

4.1.1 Cost-function for Components other than Hydropower

The specific investment cost function depends on the type and size of the project. It tends to be higher for smaller size and vice versa. It is expressed as

$$C = f \cdot P \tag{4.1}$$

Where,

C	Investment cost	$[\$]$
P	Plant capacity	$[kW]$
f	Specific cost	$[\$ \cdot kW^{-1}]$

The Equation 4.1 may be useful only if the equipment cost is larger than the erection costs and where the site-specific conditions do not influence much on the project cost. This method is, therefore, used in this work explicitly for the determination of investment costs of wind, photovoltaic power plants, battery bank and other necessary equipment. The costs of hydropower plants, on the other hand, depend largely on the hydrology, topography, geology etc. Therefore, an empiric formula is sought, which incorporates all the site-specific conditions through known variables (e.g., power and head) and unknown parameters (e.g., constant and exponent).

Figure 4.1 is shown to demonstrate the specific cost of 235 small-hydropower projects in Nepal and to define the cost-factor in Equation 4.1. It also shows the equation of the best-fit curve. This curve is used here only to illustrate the tendency of decreasing specific cost of a project with increasing capacity. However it does not give any idea about the effect of the project head and discharge [Gordon, 1983].

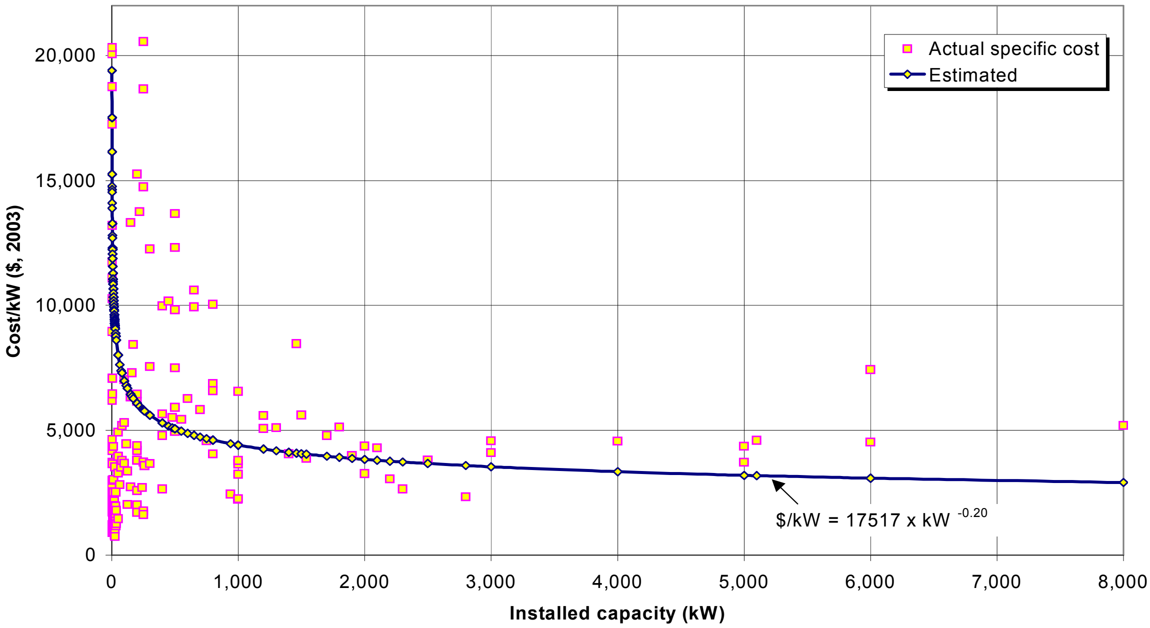


Figure 4.1: Specific cost for small-hydropower projects in Nepal

In recent years small-hydropower planning is much oriented towards reactivation and modernization of existing power plants. The motivation is that because of their proximity to load centres, technological advancement, environmental requirements, the old power plants offer great potential for economic reutilization through their reactivation and modernization. The costs of reactivation and modernization lie about 75 % and 30 % of the new construction respectively [Heimerl, 2002]. A comparative specific costs range for different installed capacities and purpose has been published by the Federal Union of German Hydropower plants (BDW) in 1994 and given in Table 4.1 for orientation purpose.

Table 4.1: Reference values for specific investments of small-hydropower plants (Price basis 1994) [Heimerl, 2002]

	Installed capacity (kW)	Investment (DM/kW)	Range of specific-investment cost (DM/kW)
New construction	1 - 100	25000	35000 - 17000
	100 - 500	18000	25000 - 15000
	500 - 5000	15000	20000 - 13000
Reactivation	1 - 100	19000	26000 - 13000
	100 - 500	14000	19000 - 11000
	500 - 5000	11000	15000 - 10000
Modernization	1 - 100	8500	10000 - 5000
	100 - 500	6000	7000 - 4000
	500 - 5000	5000	6000 - 4000

4.1.2 Cost-function for Small-hydropower Components

Several authors have expressed the investment cost of a hydropower project through mathematical function based on the statistical data. The notable parts of such functions are the constant and the exponents, which depend largely on the site conditions and thus vary from country to country. These are found by fitting the estimated curve to the investment cost data of hydropower projects from a country in question. These formulas may be used with some degree of accuracy for the preliminary project design and screening processes. In the following paragraphs the usefulness of these formulas are discussed in detail to draw recommendation for the present work.

The total actual investment costs of a project vary widely from country to country. In contrast the equipment costs are more deterministic and may be predicted with some degree of accuracy. Gordon and Penman (1979) proposes a cost-function for the project equipment. Based on which a 'site-factor' specific to the region in question may be found. It was derived from the study of 64 estimates of small-hydropower plants below 5 MW and a head below 15 m located at the existing dams.

$$C_E = k \cdot 10^3 \cdot \frac{P^{\beta}}{h_f^{\alpha}} \tag{4.2}$$

Where,

C_E	Equipment costs	$[\$]$
P	Plant capacity	$[kW]$
h_f	Design head over turbine	$[m]$
k	A constant (k =9)	$[\$]$
α	A head-exponent (α =0.35)	$[-]$
β	A power-exponent (β =0.7)	$[-]$

Equation 4.2 does not include penstocks. This is because a penstock is the item that cannot be related to the capacity and head alone but the discharge and length. Therefore, Gordon and Penman (1979) suggests classifying the hydropower project with penstock's length shorter or longer than the head over it.

Excluding penstock, it may be approximated that the costs of all other components of the small-hydropower plants depend solely on the installed capacity and head. According to Gordon and Penman it is possible to establish a relationship between equipment costs and the component costs through, the so-called site-factor (S). The site-factor depends on the installed capacity and the requirements on the water conveyance system (Penstock, canals etc.). If the equipment costs and the price index are known, then the site-factor may be determined by dividing the total project costs through the equipment costs. Considering this factor the cost of a project in Equation 4.2 takes the following form:

$$C_P = 9 \cdot 10^3 \cdot S \cdot \frac{P^{0.7}}{h_f^{0.3}} \tag{4.3}$$

Where,

C_P	Total project cost	[\$]
S	Site-factor	[–]

Furthermore, some allowance for inflation should be made to the above formula in the future estimate. Gordon classified site-factor as per the installed capacity of the project with penstock, without penstock and additional new units in a powerhouse. This is reproduced in Table 4.2 as guidance for the present and the future work. It can be seen that the site-factor tends to increase for low capacity projects with penstock.

Table 4.2: Average site-factor (S) Price basis 1979

Project	Installed Capacity	
	Below 500 kW	Above 500 kW
Without penstock	3.7	2.6
With penstock	5.5	5.1
With new units in powerhouse	1.5	1.5

It should be noted that the site-factors are based on the North American experience and hence it is recommended only for pre-feasibility assessment and must be used with caution. By fitting the estimated curve on published data of hydropower projects worldwide during 1957-82, Gordon (1983) proposes another empirical formula for total initial project cost estimation. This is similar to Equation 4.2 but best-fit was found for the higher exponent for installed capacity and lower for head.

$$C_P = k \cdot 10^3 \left(\frac{P}{h_f^{\alpha}} \right)^{\beta} \tag{4.4}$$

Where,

P	Plant capacity	[kW]
k	Constant	[\$]
α	Exponent (α =0.3)	[–]
β	Exponent (β =0.82)	[–]

The ‘constant’ k depends on both the installed capacity and the head. Therefore some range of k-values based on installed capacity and head as obtained by Gordon (1983) is repeated in Table 4.3 for reference.

Table 4.3: k-values used in Equation 4.4 (Price basis 1983)

Condition	Maximum	Average	Minimum
Development with head less than 350 m	23.0	16.5	9.9
Development with head more than 350 m	40.0	28.3	17.0
Small-hydropower below 10 MW	15.0	10.7	6.4

4.1.3 Other Cost-function used for Hydropower Optimisation

As cost-functions allow application of computer for quick iteration, many authors have tried different cost-functions for optimisation purpose. Hildebrand used for optimisation process the following the cost-function based on capacity as single variable:

$$C_P = aP^{\beta} + k \tag{4.5}$$

Where,

P	Plant capacity	$[kW]$
k	Constant	$[-]$
a	Coefficient	$[-]$
β	Exponent <1	$[-]$

The main reason for the use of the Equation 4.5 with exponent less than 1 was to obtain the concavity of the cost-function. It is difficult to use the branch and bound method if a cost-function using exponent > 1 has convexity. However, Hildebrand points out that the convexity may be faced at the difficult sites. Moreover in some cases discontinuity in the cost-function may prevail. As an example in an extremely low-head hydropower plant with large design discharge and greater capacity either the number of turbine must be added or other type of turbines must be selected [Hildebrand, 1993].

Zelalem also used a cost-function based on installed capacity as single variable. In the framework of the research project IKARUS in Germany, Giesecke et al (1993) recommend empirical cost-functions for various components of a hydropower project, which are valid for projects with installed capacity below 2 MW and head below 15 m. It is out of present aim to discuss all the cost-functions in detail. Therefore, they are summarized and presented in Appendix I Table A.2 as guidelines for future works.

By observing Table A.2 in Appendix I it may be remarked that by changing constant and the exponent, a site specific-cost-function may be developed for a project in question. If the equipment cost is known then the site-factor for each of the projects can be determined [Gordon and Penman, 1979]. It is suggested to conduct a comparison between all of the formula before attempting to use any one of them. Zelalem (2002) did a comparison of equipment costs using formula suggested by Harvey (1993), Gulliver and Dotan (1984) and Giesecke et al (1993). According to him Harvey's formula gave a very low value of cost, whereas the values obtained from formulas suggested by Giesecke and Gulliver compared quite well.

For the present work the k-values and S factors have been determined with respect to installed capacity and head of various small-scale hydropower projects using Equation 4.3. This was based on the statistical data of 91 hydropower projects planned and constructed in different regions of Nepal since 1981. The 'constant' k and the site-factors have been classified according to the installed capacity and the design head in Table 4.4.

Table 4.4: k-values for Nepalese hydropower project costs (Price basis 2003)

Project type according to installed capacity	Project type according to design head	Factor	Maximum	Average	Minimum
Pico to micro-hydro (1 kW-100 kW)	h_f > 50 m	K	46.25	12.04	5.63
		S	5.14	1.33	0.63
	15 <h_f < 50 m	K	49.10	10.93	3.05
		S	5.46	1.22	0.34
	h_f < 15 m	K	39.57	6.77	2.22
		S	4.40	0.75	0.25
Mini to small-hydro (1 MW-10 MW)	h_f > 50 m	K	46.79	24.53	8.38
		S	5.20	2.73	0.93
	15 <h_f < 50 m	K	58.77	28.38	9.33
		S	6.53	3.15	1.04
	h_f < 15 m	K	N.A	N.A	N.A
		S	N.A	N.A	N.A

h_f : Net head over turbine. NA.: Data not available.

The Rural Energy Development Program of UNDP/Nepal has built most of the projects below 100 kW using advanced technologies for demonstration purpose [REDP, 2004]. Other values were collected from different sources [NEA, 2001, 1997, NEA/GTZ, 1993, 1996, Shrestha and Schmidt 1992] these values are presented in Table 4.4.

In the observed projects the head ranges from 5 m to 215 m and the power ranges from 1 kW to 10 MW. As may be noticed the k and S values increase for medium-head projects. Comparing k-values in Table 4.2 and in Table 4.4 respectively one may notice that the k-values for Nepalese hydropower are, in order of magnitude, higher. This may be due to the price escalation to 2003 for Nepalese hydropower projects. The site-factors were derived from international hydropower projects (see Table 4.2) indicating the general applicability of Equation 4.3 for the Nepalese hydropower projects. The cost data for head h_f < 15 m in mini to small-hydro range were not available. Figure 4.2 is a plot of the project costs against the $P/h^{0.3}$ for 91 projects planned or constructed during the period 1981 to 2003 in Nepal.

The actual costs were escalated at inflation rate of 8.7 % to the year 2003. As will be noticed the actual costs of the projects up to 50 kW fairly cluster towards the minimum value of k whereas the actual costs of projects above 250 kW cluster towards the maximum value. This may be explained as the size of the project increases the costs of electro-mechanical equipment and penstocks increases sharply than the cost of civil works. Many projects fewer than 50 kW have simple hydraulic structures and mechanical control equipment and have been developed using local construction and manufacturing technologies. On the other hand, some projects below 30 kW also fall within the envelope of the average and maximum k-lines. The reason may be either the application of sophisticated electronic control equipment or the remoteness of the project sites or both.

The breaks in the k-lines denote the missing data for head and discharge for projects between 50 kW to 250 kW.

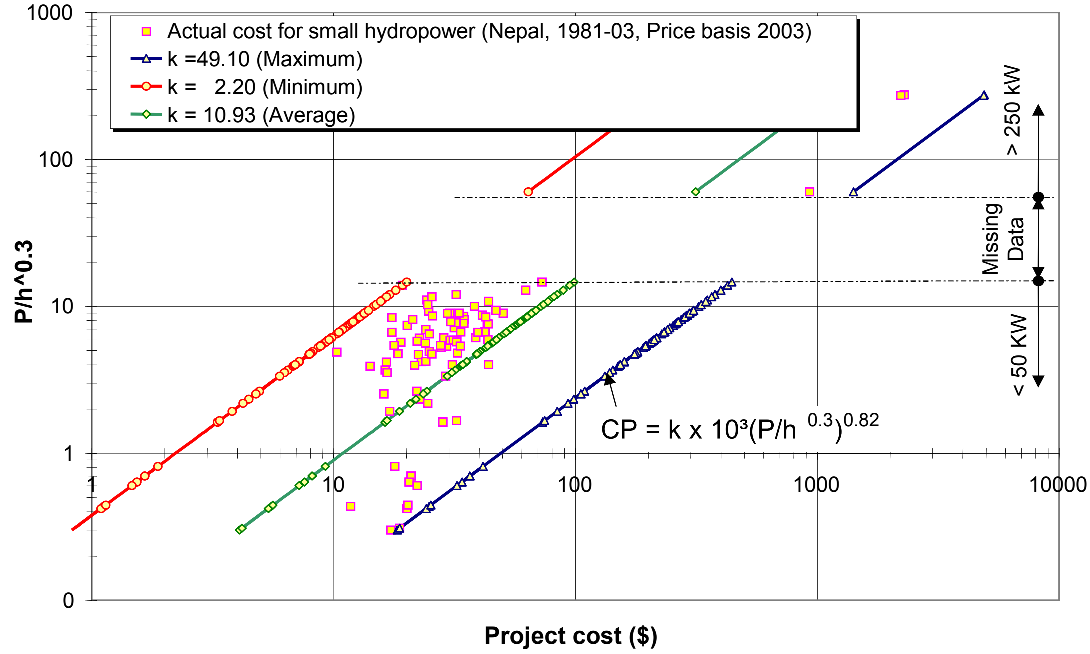


Figure 4.2: Determination of k values for small-hydropower projects in Nepal

To examine the effect of the project size (capacity and head) on the project cost and to evaluate qualitatively the cost of Nepalese hydropower in the context of international hydropower projects, the author has superimposed the published data by Gordon (1983) on Figure 4.3.

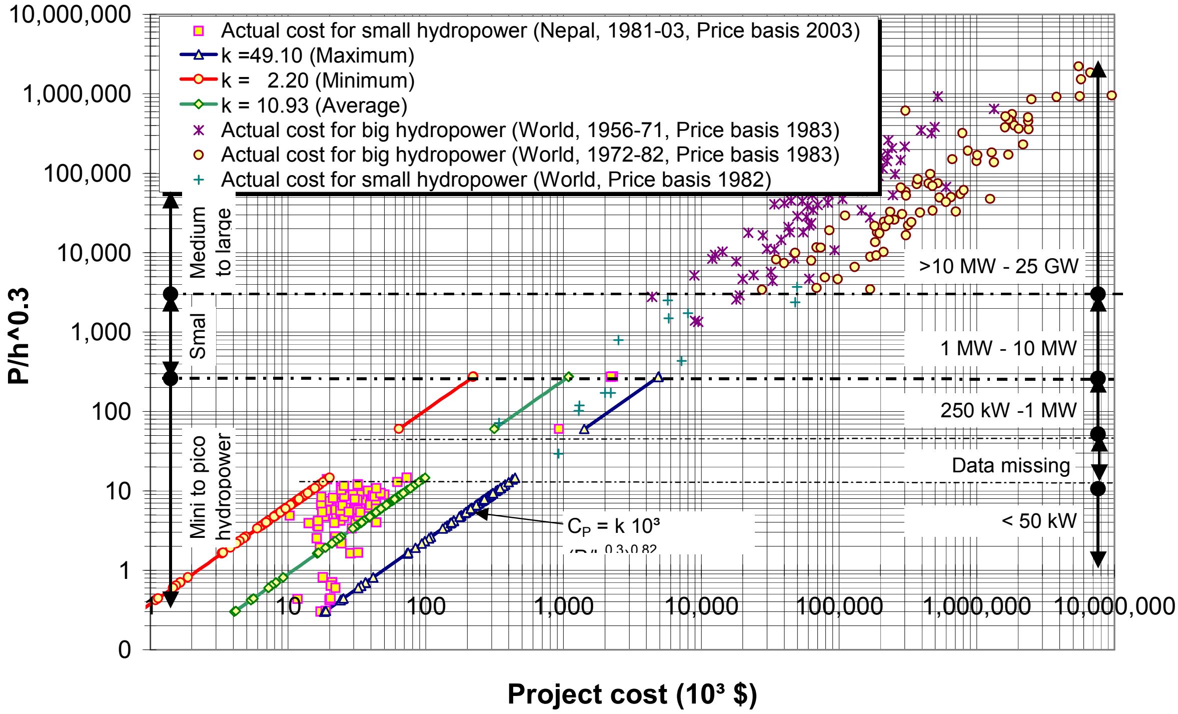


Figure 4.3: Qualitative costs comparison between the Nepalese and the international hydropower projects

The international cost data were not escalated to the price basis 2003. Therefore only a qualitative conclusion from this exercise may be made. As can be seen from Figure 4.3, most of the actual costs of projects constructed worldwide during 1957-1971 fits quite well within the envelop of the average and maximum k-lines of Nepalese hydropower projects. Other projects constructed during 1972-1982 move towards right. The reason may be the price escalation, costly equipment and the remoteness of the site. This indicates that for the cost estimation of new hydropower projects in Nepal the k-value should approach towards the maximum. Further, the k-value does not remain constant because of price escalation and it should be taken carefully based on engineering and economic judgment. A summary of statistical data for various randomly selected hydropower projects worldwide is presented in Table 4.5.

Table 4.5: Summary of statistics for various randomly selected hydropower projects planned and constructed worldwide.

Country	Type and period	Number of projects	Statistical range	Capacity (kW)	Head (m)	$\frac{P}{h^{0.35}}$	Actual project cost (10^3 \$)
Nepal[8]	Pico to small (1981-03) Price basis 2003	91	Maximum	996	212	224	2,291.00
			Minimum	1	6.5	10.3	10.30
			Average	39.43	40.2	10.2	87.16
			Std. Dev.	142.62	34.5	32.3	340.51
World[9]	Mini to small (1957-82) Price basis 1983	13	Maximum	10,000	244	3,713.5	49,700.00
			Minimum	170	11	29.4	340.00
			Average	3,613.8	86.5	1,053.3	10,380.80
			Std. Dev.	3,654	78	1,202	17,259.00
	Medium to big (1957-71) Price basis 1983	74	Maximum	3,105,000	1290	933,437	1,338,000.00
			Minimum	11,000	7	1,345	4,400.00
			Average	406,700	177.7	89,541	135,388.00
			Std. Dev.	569,000	229	144,706	190,449.00
	Medium to big (1972-82) Price basis 1983	81	Maximum	25,000,000	1100	4,550,508	13,000,000.00
			Minimum	11,000	5.7	3,427	27,600.00
			Average	1,563,200	165.3	353,676	1,617,168.00
			Std. Dev.	3,455,000	204	749,190	2,755,623.00

Std. Dev.: Standard deviation

[8] Author's own investigation in to various published hydropower data from Nepal.
[9] Gordon, 1983, Water Power and Dam Construction

The double logarithmic presentation (see Figure 4.4) shows good correlation between actual and calculated values.

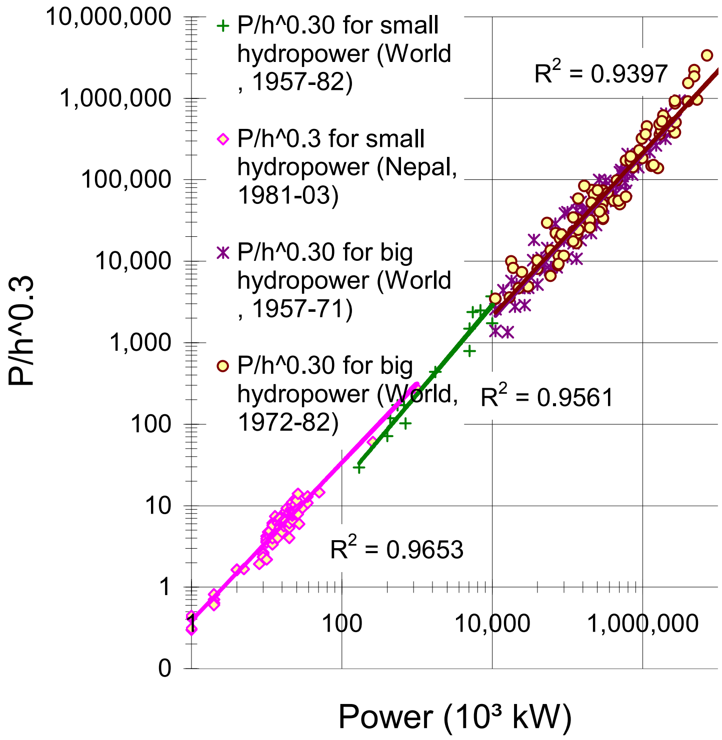


Figure: 4.4: Installed capacity vs. $P{\cdot}h^{-0.30}$ factor

The k-values for medium-head and high-head hydropower projects tend to increase. Consequently, the project cost increases. Gordon (1983) noticed that there exists no simple explanation for this increase. He speculates the cause may be the nature of the Equation 4.40, where the numerator becomes too large as head increases. Further, high-head projects usually include more expensive geological investigation and underground structures than low-head projects. This is the case for medium to large-scale projects. For small and micro-hydropower projects the equation behaves differently.

It was found that, depending upon the installed capacity, the k-values change for each type of design head. Hence the project cost changes accordingly. To examine this finding, the dependency of $P{\cdot}h^{-0.30}$ factor and k-values on the project capacity and head will be discussed in the following paragraphs. Three separate curves were fitted against the actual project costs to classify the project according to their installed capacity and head in Figure 4.5.

The $P{\cdot}h^{-0.30}$ values increase potentially as the installed capacity increases. Theoretically all the points should plot parallel. As will be noticed the slopes of these curves for different head-ranges and capacities are not same. This may explain why in the medium to big hydropower project regions, the k-lines for medium-head projects shift towards the right and supersedes both the high-head and low-head projects respectively. This implies that the medium and high-head projects are more expensive than the low-head projects.

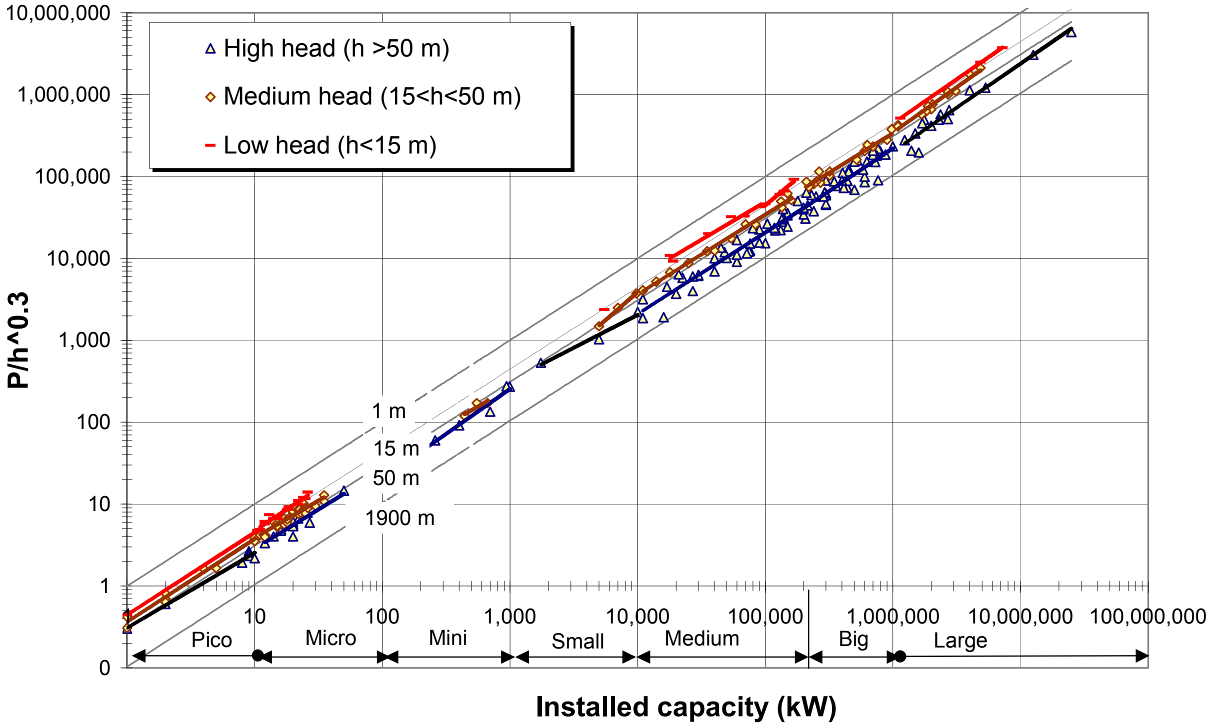


Figure 4.5: Relationship between installed capacity and $P \cdot h^{-0.30}$ factor

It seems that high-head projects are more favourable followed by the medium and the low-head projects in the small-hydropower regions. In the pico to micro-hydro region high-head projects are more expensive than medium and low-head projects. However, more data are necessary to support this argument. This conclusion indicates that both installed capacity and head should be considered for optimisation of hydropower capacity.

Finally, Table 4.6 presents a summary of the above discussion in simple matrix form. It shows the dependence of the project cost on both capacity and head. Therefore, for the economic analysis both power and head have been used in the present work.

Table 4.6: A simple matrix for evaluating project costs as a function of k and $P \cdot h^{-0.30}$

Project type	Pico to Micro-hydro						Mini to Small-hydro						Medium to Large-hydro					
Head (m)	Low		Middle		High		Low		Middle		High		Low		Middle		High	
Factor	x	k	x	k	x	K	x	k	x	K	x	k	x	k	x	k	X	k
Head increase	D	I	D	I	D	I	NA	NA	D	D	D	D	I	D	D	D	D	I
Capacity increase	I	D	I	D	I	D	NA	NA	I	D	I	D	I	I	I	D	I	I
Project cost depends on	Power and head		Power and head		Power and head		NA		>Power and < head		>Power and < head		Power and head		>Power and < head		Power and head	

Note: $x = P \cdot h_f^{-0.30}$; D - Value decreases; I - Value increases; NA – Data not available.

4.1.4 Cost Function for Mini-Grid

The transmission line costs depend on the length, voltage- and current capacity, materials of conductor, and terrain. The following cost-function [Happoldt and Oeding, 1978] is generally applied for the determination of the cost of a 3-phase double-conductor transmission line as shown in Figure 4.6 c with transmission voltage $U_N \geq 110$ kV:

$$C_{Tr} = C_{Const} + C_U \cdot U_N + C_{Cond} \cdot A_{Cond} \cdot \sqrt[4]{n} \qquad (4.6)$$

Where,

C_{Tr}	Total specific-cost of transmission line	$[\$ \cdot kW^{-1}]$
C_{Const}	Specific-cost for planning, laying and repair	$[\$ \cdot kW^{-1}]$
C_U	Cost per voltage per kilometre length	$[\$ \cdot kV^{-1} \cdot km^{-1}]$
U_N	Nominal voltage	$[\$ \cdot kW^{-1}]$
C_{Cond}	Cost of conductor per kilometre length	$[\$ \cdot km^{-1}]$
A_{Cond}	Total cross-sectional area of conductor	$[mm^2]$
n	Number of conductors in a bundle ($n \leq 4$)	$[-]$

The fluctuation in costs estimated by the Equation 4.6 lies in the range of 70 to 160 % (!) [Happoldt and Oeding, 1978].

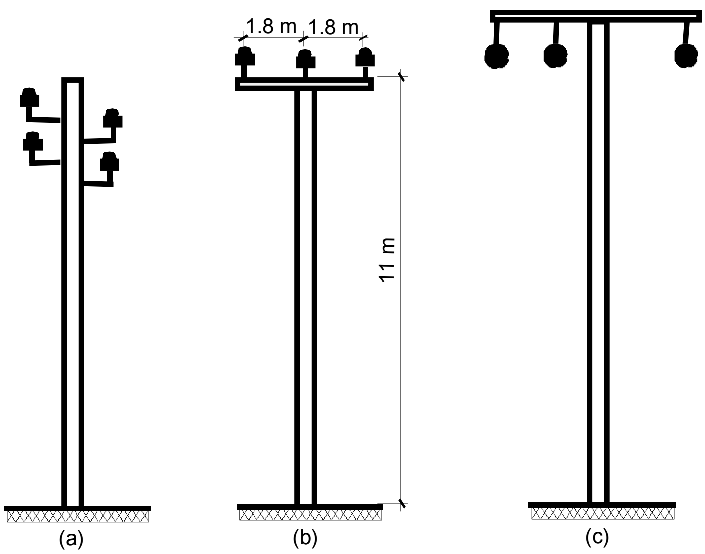


Figure 4.6: Masts for 3-phase rotating current transmission lines. (a) Low-voltage transmission on wooden mast with neutral conductor; (b) Medium-voltage transmission on concrete mast; (c) High-voltage transmission up to 110 kV on concrete mast with conductors in bundle.

For a single 3-phase 33 kV transmission line as shown in Figure 4.6 a, and b the following relationship is suggested [Happoldt and Oeding, 1978]:

$$C'_{Tr} \approx 0.67 \cdot C_{Tr} \tag{4.7}$$

The Equation 4.8 has been used for the modelling of power system in this work. This formula is only indicative and should be used with precaution because voltages above 110 kV would only very seldom be used unless for main transmission lines in national grids. Therefore, the Equation 4.8 has less relevance with mini-grids and stand-alone plants. It is thus desirable to find a cost-function for mini-grid based on statistical analysis, which is omitted here due to the lack of data.

5 RENEWABLE POWER SYSTEM MODELLING

5.1 Renewable Power Systems for Rural Electrification

As has been discussed in Chapter 1, the renewable power systems for rural electrification envisage mainly the integration of multiple power generators and multiple power consumers. These power generators may include, where appropriate, small hydropower plants and (bio)-diesel power plants. They may also include wind power plants and photovoltaic power plants etc. together with energy storage facilities. In some literature these systems are also known as distributed generations, decentralized generations, hybrid power generations etc [Manuwell et al, 1998, Schmidt and Bard, 2002, Petrie et al 2003]. Table 5.1 presents a general classification of renewable power systems for rural electrification according to power range and voltage demand of consumers and its purpose as adopted in this work.

Table 5.1: Classification of renewable power systems for rural electrification need

Type of power system	Power Demand	Voltage range and type of transmission line	Purpose
Low-voltage	< 100 W	6 V – 48 V (DC) Two-wire system	• Small households appliances • Battery charging stations • Uninterrupted power supply (UPS)
	100 W – 1 kW	12 V (DC) – 1-Φ 230 V (AC) Two-wire system	• Individual home electrification • Solar home system, wind home system • Pico-hydropower pack • Micro-scale hybrid power generation
	1 kW – 5 kW	1-Φ 2-wire 230 V (AC) – 3-Φ 400 V (AC)	• Small community electrification • Cottage industries • Powerhouse own energy need
Medium-voltage (Linguistic usage)*	5 kW – 100 kW	3-Φ 3-wire or 4-wire 400 V (AC) – 3 kV (AC)	• Rural electrification at community level (mini-grid system with single generating unit) • Medium-scale industries
	100 kW – 1 MW	3-Φ 3-wire or 4-wire 3kV – 11 kV (AC)	• Rural electrification at villages level (Isolated grid with more than two generating units and interconnection with public grid system at district level) • Medium-scale industries
	1 MW – 10 MW	3-Φ 3-wire 11 kV – 33 kV (AC)	• Rural electrification at district and regional level (Isolated grid with two or more generating units and interconnection with public grid system) • Large-scale industries

Note: * Above 1 kV level is classified as High-voltage in Europe [Hapoldt and Oeding, 1978]. Φ-Phase; DC- Direct current; AC- Alternating current; V-Volt; kV- kilovolt (1000 V); W-Watt; kW- kilowatt (1000 W); MW- Megawatt (1000 kW).

As noticed, the power demand of a system may range from few watts to megawatt depending upon the purpose and level of electrification. While a low-voltage power system is generally suitable for house-hold appliances, a reliable village level rural electrification may be achieved through clustering several small hydropower plants and renewable energy technologies in medium-voltage type power systems.

In the present work, a hydropower-based power system with renewable energy technologies (wind and photovoltaic power plants) and energy storage facility (battery bank) has been modelled. The concept of small hydropower-based power system and the rationale for utilization of renewable energy technologies have been discussed in Chapter 1. Before going into the details of its model description, it is expedient here to briefly review the inherent characteristics of renewable energy sources and technologies.

5.2 Comparative Study of Renewable Energy Sources and Technologies

Unlike the fossil fuels oriented energy alternatives, the generation of electrical energy from renewable technologies is characteristically dependent on the hydro-meteorological conditions of a project site. Therefore, a hydro-meteorological comparison of these renewable energy sources is imperative in order to appraise the technologies based on these sources.

Keeping in mind the possibility for generating electrical energy from other renewable energy sources such as biomass (bio-diesel, bio-gas etc.), geothermal etc., the present aim is to discuss only the hydro-meteorological and technical characteristics of hydropower, wind and photovoltaic technologies. Kaltschmitt and Wiese (1997) provide a detail comparison between all of these technologies. Based on their work the following arguments for small hydropower-based power system have been summarized.

One way is to discuss both time and space dependencies of hydro-meteorological characteristics of water, wind and solar energy sources. Therefore, their comparison should be made not only for the time-series distributions but also for the spatial distributions as shown in Figure 5.1. The monthly, daily and hourly fluctuations of wind velocity distribution over a year and over a week respectively are ‘noisy’ as compared to solar radiation and water discharge during the same period of time. However, the average wind velocity is higher in winter period than in summer. Just opposite is the case with solar radiation. The average monthly value of solar radiation rises steadily to its maximum during the summer periods. Its typical hourly distribution limits the use of solar energy only for few hours a day.

The river discharge, on the other hand, is high during the beginning of the year due to snow melting (for example in Alps region) and drops steadily during the summer time to its minimum at the end of the year (Figure 5.1 left). However the hourly distribution of water discharge is constant over a week or even month as compared to solar radiation and wind velocity (Figure 5.1 right). These examples are typical for Germany. However, it may be generally concluded that there is a possibility for integrated use of wind, water and solar energy for smooth operation of power system by combining wind, solar and hydropower in other countries.

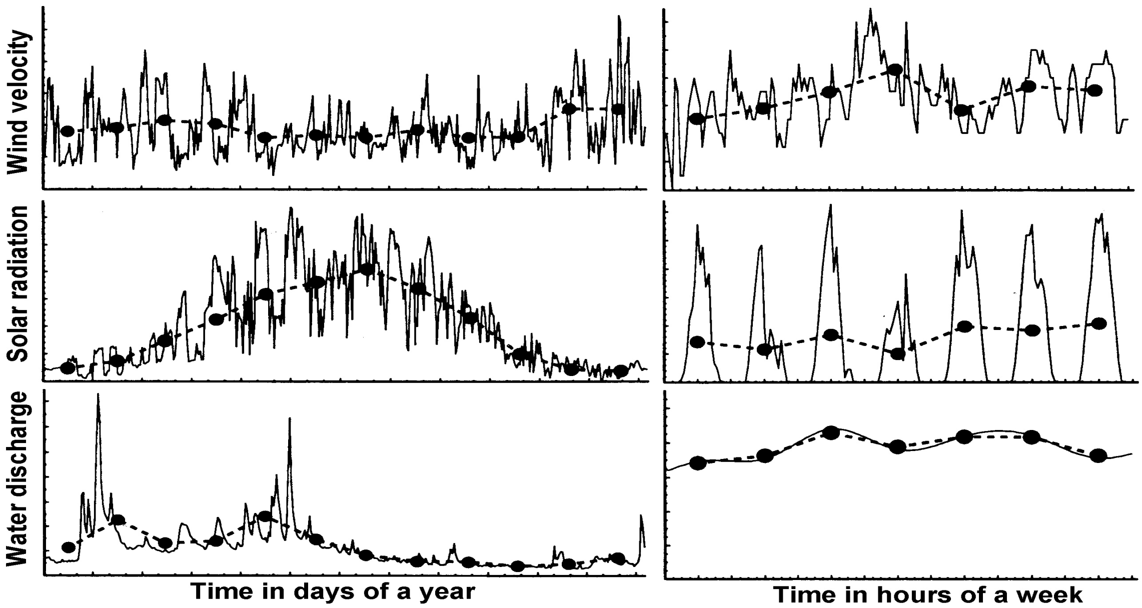


Figure 5.1: Hydro-meteorological characteristics of wind velocity, solar radiation and water discharge with respect to time in days of a year or hours of a week. Thick lines indicate the monthly and daily average values respectively [Kaltschmitt and Wiese, 1997]

It has been observed that the spatial distribution of long-year average wind velocity is higher in the northern coastal regions than in the southern regions of Germany. Just opposite is the case due to the good water discharge availability in the rivers and the suitable hilly topography of the southern regions, the hydropower potential is higher than in the northern regions. Because of the geographical and topographical conditions, the long-year average velocity and the water discharge fluctuates highly within a small regions. Due to its relatively closeness to the Equator, the southern regions have higher solar energy potential than northern regions. However, local variation in solar radiation supply may be observed due to local weather change (e.g., during a cloudy day).

For example, Figure 5.2 (a) shows of a 2 min. averaged wind velocity recorded for a day in February 2001 at a camp near Jomsom airport in Nepal [Egger et al, 2002) Even though the wind fluctuates within this short period, enough wind energy may be harvested (Generally an average wind speed above 5 m/s is necessary in order to harvest any significant amount of power with respect to the size of the turbine) during daytime after 10:00 to 18:00 local time standard (LST) and few hours in the night. Figure 5.2 (b) shows the details of the short time fluctuation in wind velocity and solar radiation with respect to air temperature. It is to be noted here that wind power is proportional to the cube of the wind velocity; any change in wind velocity will highly influence the power production from a wind turbine. The photovoltaic power plant is also very sensitive to intensity of the solar radiation. Since gusty wind and clouds may vary instantly, it is necessary to analyse wind and photovoltaic power production in minute interval as possible. In such a short period water discharge of a river does not vary much and hence the power production from hydropower remains practically constant throughout the day.

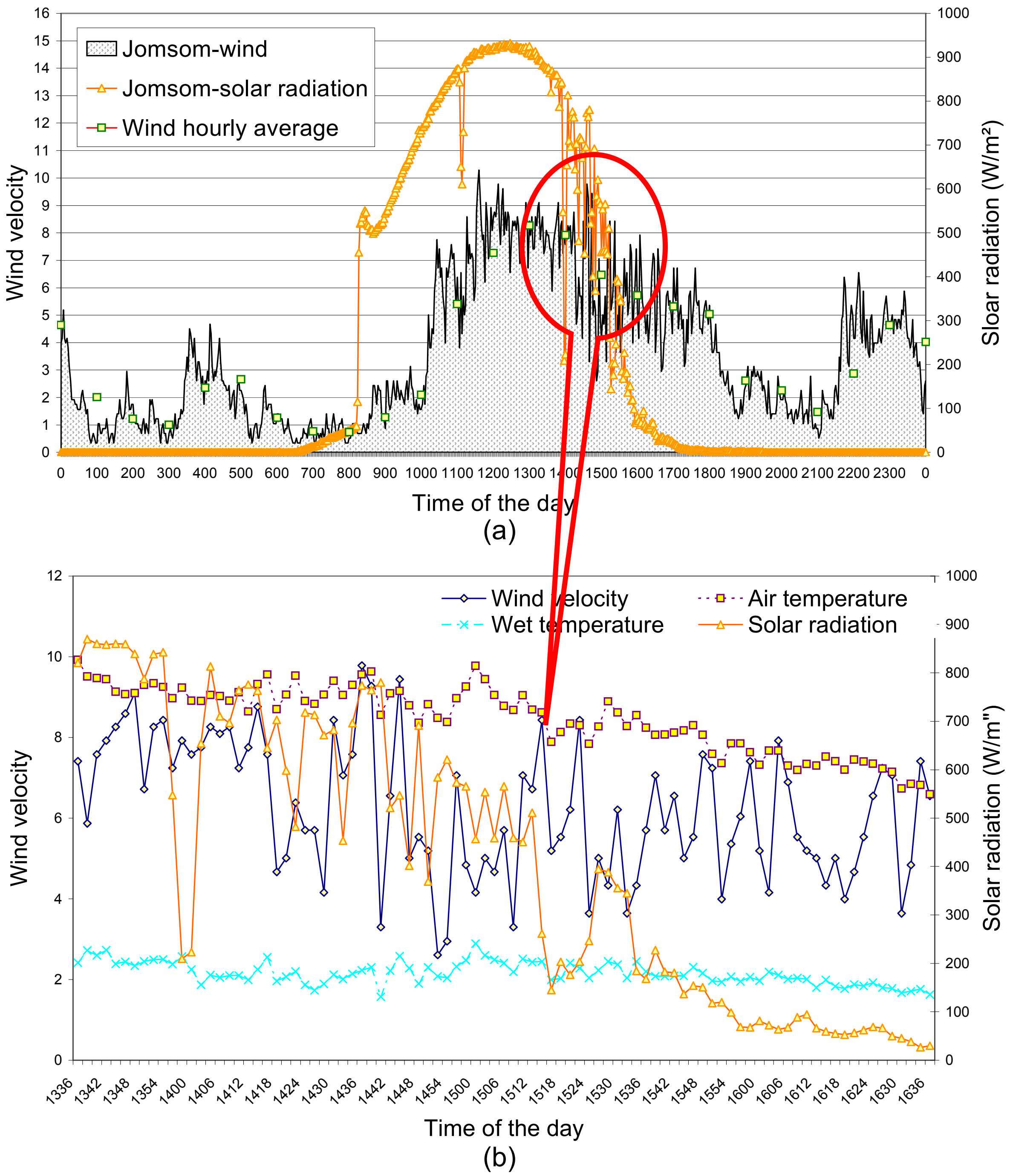


Figure 5.2: (a) Wind velocity and solar radiation (2 min. averaged) recorded for a day in February 2001 at Jomsom airport in Nepal, (b) Enlarged view of the time-series fluctuation of wind velocity and solar radiation [Eager et al, 2002].

Figure 5.3 presents the spatial distribution of wind velocity recorded within the same time for five places of Kaligandaki valley (Tukuche, Marpha, Jomsom, Kagbeni and Lo Manthang). These places are located within a distance of 10-15 km from each other in Annapurna Region of Mustang district in Nepal.

It is clearly seen that the up-valley wind velocity increases from South (starting from Tukuche at 2700 m.a.s.l) to North with the altitude up to Kagbeni (at 2900 m.a.s.l) and then decreases further North at Lo Manthang (at 3800 m.a.s.l) [Data support from Prof. Egger, University of Munich].

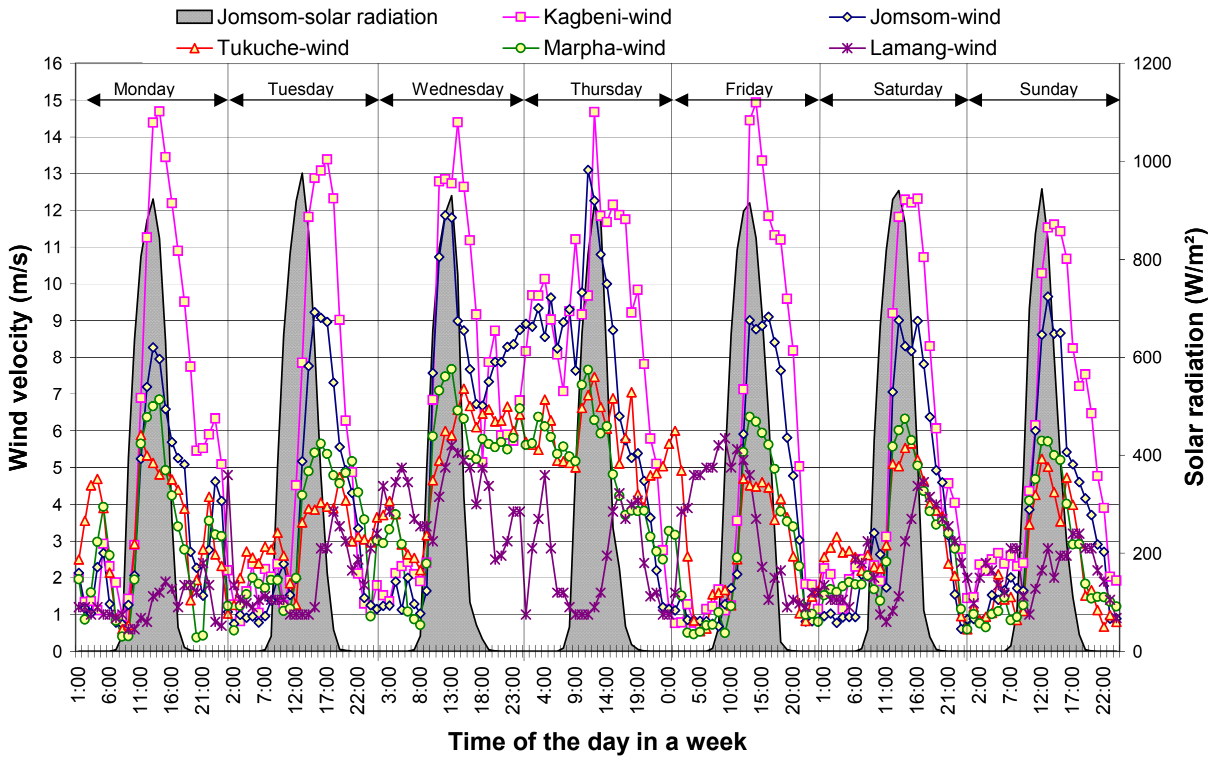


Figure 5.3: Hourly average wind velocity recorded for a week in February-March 2001 at various places in Mustang district in Nepal. The hourly average solar radiation at a camp near Jomsom airport is also superimposed. Data support from Prof. Egger, Meteorologisches Institut, Universität München, Continental Consultant, 1985.

Based on their series of field survey, Egger et al (2000, 2002) observed that the Kaligandaki valley wind system poses two diurnal characteristics: a strong asymmetric in wind velocity between day and night and extreme intensity of wind velocity. Strong up-valley wind has been observed daily between 8:00 and 10:00 LST reaching a peak velocity of 14-15 $m \cdot s^{-1}$ approximately at 14:00 LST, which decays later as the sun sets down (see Figure 5.3). The nocturnal down-valley flows were observed quite weak. However the accelerated up-valley wind was observed only in the core region (Marpha-Kagbeni) as compared to entrance region (Ghasa-Tukuche) and exit region (Chuksang-Lo Manthang). Zängel et al (2001) used computer simulation to describe this phenomenon. This observation led them to conclude that the dynamics of Kali Gandaki valley wind regime cannot be explained on the basis of hydraulic flow theory [Egger et al 2002].

From the power utilization point of view, the time-series wind distribution in this region is fairly compensatory. A longer wind energy harvest may be possible if a decentralized power system were designed interconnecting the southern regions with northern regions. The solar radiation recorded at the camp near Jomsom airport has been superimposed to analyse the effect of combined operation.

It is seen even though the higher wind velocities and higher solar radiation occur nearly at the same time of the day; there is a possibility to supply energy throughout the week by combining these sources. Moreover, the hydropower potential in the southern middle hilly regions is higher than the northern mountainous regions (refer Chapter 7), which again exemplify the need to consider a regional power system.

Due to different meteorological supply characteristics of renewable energy sources, the electricity production using these technologies also highly differs. Figure 5.4 shows, as an example, the effect of fluctuation in energy sources on the production of electricity. Comparing it together with Figure 5.1, it may be said that the annual electricity production by a photovoltaic power plant is somewhat better than the electricity from a wind turbine. The variation in annual production by photovoltaic plant is marginal and the daily and annual courses are highly distinct. The annual electricity production from a run-of-river hydropower plant is partially distinct. The hourly and daily fluctuation in electricity production from wind is higher than from photovoltaic plants. Such fluctuation in power production from hydropower is little to marginal.

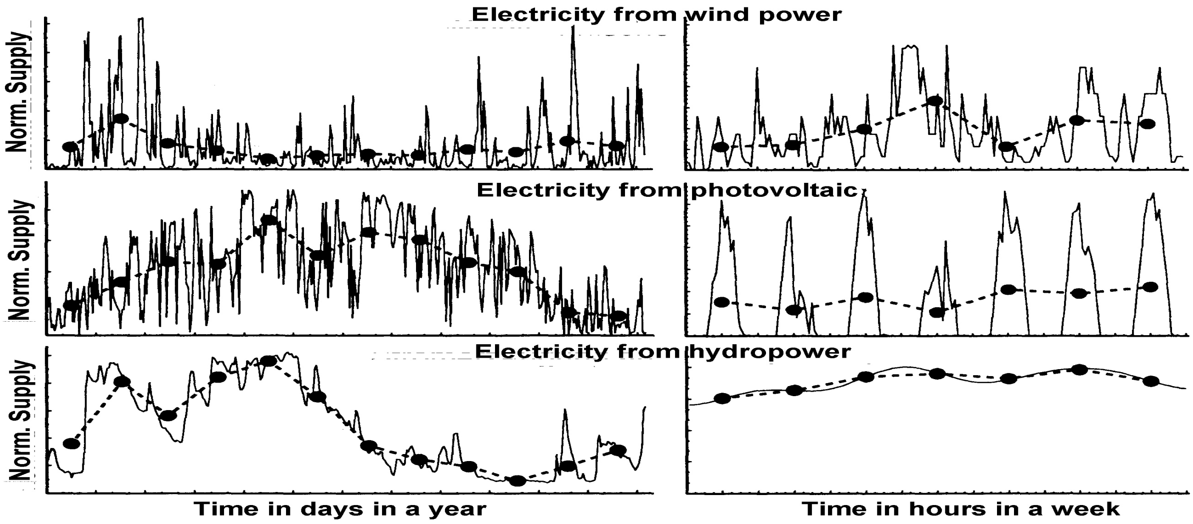


Figure 5.4: Normalized power supply curve for wind, photovoltaic and hydropower technologies [Kaltschmitt and Wiese, 1997].

Another way for characterizing the renewable energy sources is to define it through the power density (kW/m²). Table 5.2 presents power density of hydropower, wind and photovoltaic technologies. As seen the power density of hydropower at 6 m/s velocity of water is significantly higher than wind and solar.

Table 5.2: Summary of meteorological and technical characteristics of hydropower, wind and photovoltaic power plants [Giesecke and Mosonyi, 2003; Kaltschmitt and Wiese, 1997].

Characteristics	Parameters		Hydropower	Wind power	Photovoltaic
Meteorological	Power density [$kW \cdot m^{-2}$]		108 at 6 $m \cdot s^{-1}$	0.13 at 6 $m \cdot s^{-1}$	0.25 (On the horizontal surface on earth)
				1.04 at 20 $m \cdot s^{-1}$	
	Fluctuation	Min.	None	Extremely high	Very high
		Hour	Marginal	Extremely high	Very high
		Day	A little	Very high	high
	Variation	Annual	High	High	Marginal
	Daily course		None existent	Less distinct	Highly distinct
	Annual course		Partially distinct	None distinct	Highly distinct
Technical	Typical capacity (kW)		1 - > 100,000	1 - > 1,500	Few watts – 1,000
	Average System's efficiency (%)		>70	19 - 33	4 - 12
	Availability (%)		99	95 - 97	95 - 97
	Average utilization period		4,500 – 6,500	1,400 – 3,200	800 - 1,020

Table 5.2 also summarizes the technical characteristics of different energy sources. It is seen that the average utilization period and the system's efficiency of a hydropower plant are significantly higher than the other two. Hence, small hydropower is suitable for base-load operation in an isolated rural electrification with renewable energy technologies. Photovoltaic and wind power may be used for covering the intermediate or peak load incorporation with energy storage facilities [Cavallo, 2001]. It is to be noted here that all stall regulated wind turbines are designed for stall velocities of 10-14 m/s, thus in practical life it give little meaning to provide the power at 20 m/s. Pitch controlled turbines will show only slightly higher captive ranges.

Following sections present descriptions of system components and their physical parameters.

5.3 Power System Components

5.3.1 Overview of Computer-based Simulation Model

To simulate and optimise different components of a power system, a large number of decision variables and their combinations should be iterated and evaluated against boundary constraints.

At present, a computer-based simulation of power system's components necessary for rural electrification has been developed and tested in the Microsoft Excel 2000 spreadsheet.

An overview of the Decentralized Power System Simulation and Optimisation Model (DEPSO) using Microsoft Excel software is presented in Figure 5.5.

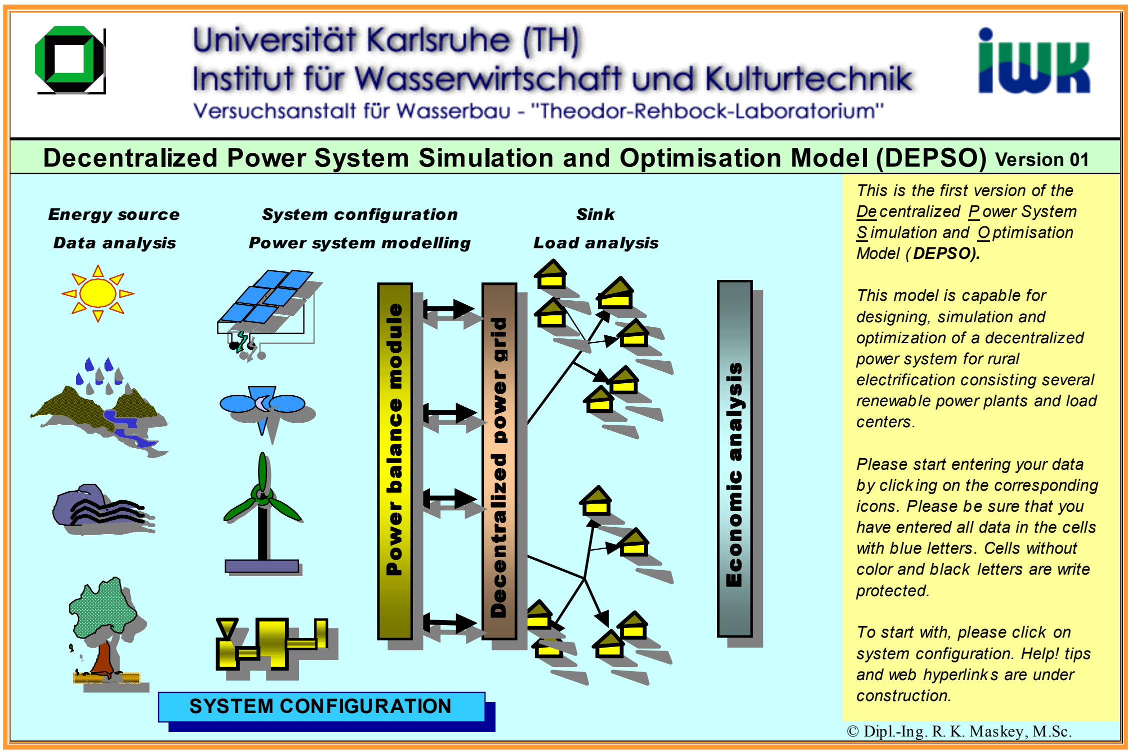


Figure 5.5: A Decentralized Power System Simulation and Optimisation Model

As can be seen, the developed model DEPSO (Decentralized Power System Simulation and Optimisation) consists of several components from power generation and consumption. It includes appropriately alternating current (AC) and direct current (DC) sources, a transmission and distribution system, energy converters, energy storage facilities and several primary, secondary and deferrable loads. The structure of this virtual power system is designed to simulate the structure of the actual power system as closely as possible.

In this Chapter, the model DEPSO is applied to simulate and optimise the technical and economic performances of 6 small hydropower plants with or without wind or photovoltaic power plants. This model can also integrate other renewable energy technologies wherever is applicable. The simulation and optimisation procedures of this model will be described in Chapter 6 and its application is presented in Chapter 7.

The power system components represented by the DEPSO model consists of 8 modules as follows:

1. Energy data analysis module
2. System configuration module
3. Hydropower plant module
4. Photovoltaic plant module

5. Wind power plant module
6. Mini-grid module
7. Consumers load analysis module
8. Economic analysis module

Due to modular structure of the DEPSO, a wide range of power sources and data analytical tools can also be integrated as per the need. At present, the energy source data analysis module is integrated directly into the respective modules of energy technologies.

Following sections present a detail description of each of the modules mentioned above.

5.3.2 System Configuration Module

System configuration module is designed as a supervisory control frame. This module is used for the simulation and optimisation process by visualizing the input and output data in one window. The data entry begins at the system configuration module. It mainly consists of the following information:

Project information: It stores information on project name, its location coordinates, date of the program execution and the name of the system analyser. This information is automatically copied to each of the modules for easy identification of the results in each module.

System configuration: It consists of system's preliminary configuration such as with or without regional grid, type of grid, type of energy generation schedule and type of system components. To provide flexibility in configuring the system components, the drop-down menu provides possibility for selecting appropriate plants. For economic analysis of energy production, it is also made possible to select either central or isolated mode of operation. At present, the following system components can be set by such operation:

1. System load (at each power off-take node)
2. Transmission line (at each line stretch)
3. Hydropower plant (at each power intake node)
4. Solar power plant (at each power intake node)
5. Wind power plant (at each power intake node)
6. Battery bank (at each power intake node)
7. Secondary loads (at each power off-take node)

For analysing the stability of the results for variable loads, it is also desirable to check sensitivity of the performance of a DPS on variable loads.

5.3.3 Hydropower Plant Module

5.3.3.1 Basics

The module for hydropower plant is designed to evaluate both the single and several hydropower plants ranging from few kW to 10 thousands of MW capacities. The following paragraphs should highlight model algorithms in detail.

In general a computer-supported hydropower model should ideally consider all of site conditions and equipment use. On the other hand, one should be aware of the fact that the consideration of all variables may complicate the modelling process and slow down its performance. It is a matter of experience on the selection of those factors, which are directly relevant for simulation and optimisation. As has been discussed in Chapter 4, the empirical cost-function for hydropower is based on two variables: installed capacity and the head. At present only those components of a run-of-river hydropower station have been chosen as the decision variables that are directly dependent on either head or discharge or both of them together. For example the design of dam, reservoir, sand-trap, forebay, powerhouse etc. have been omitted.

Figure 5.6 (a) shows an example of a typical diversion type high-head small hydropower plant. Figures 5.6 (b) show typical low-head run-of-river type hydropower plants with fish ladder or fish bypass channel.

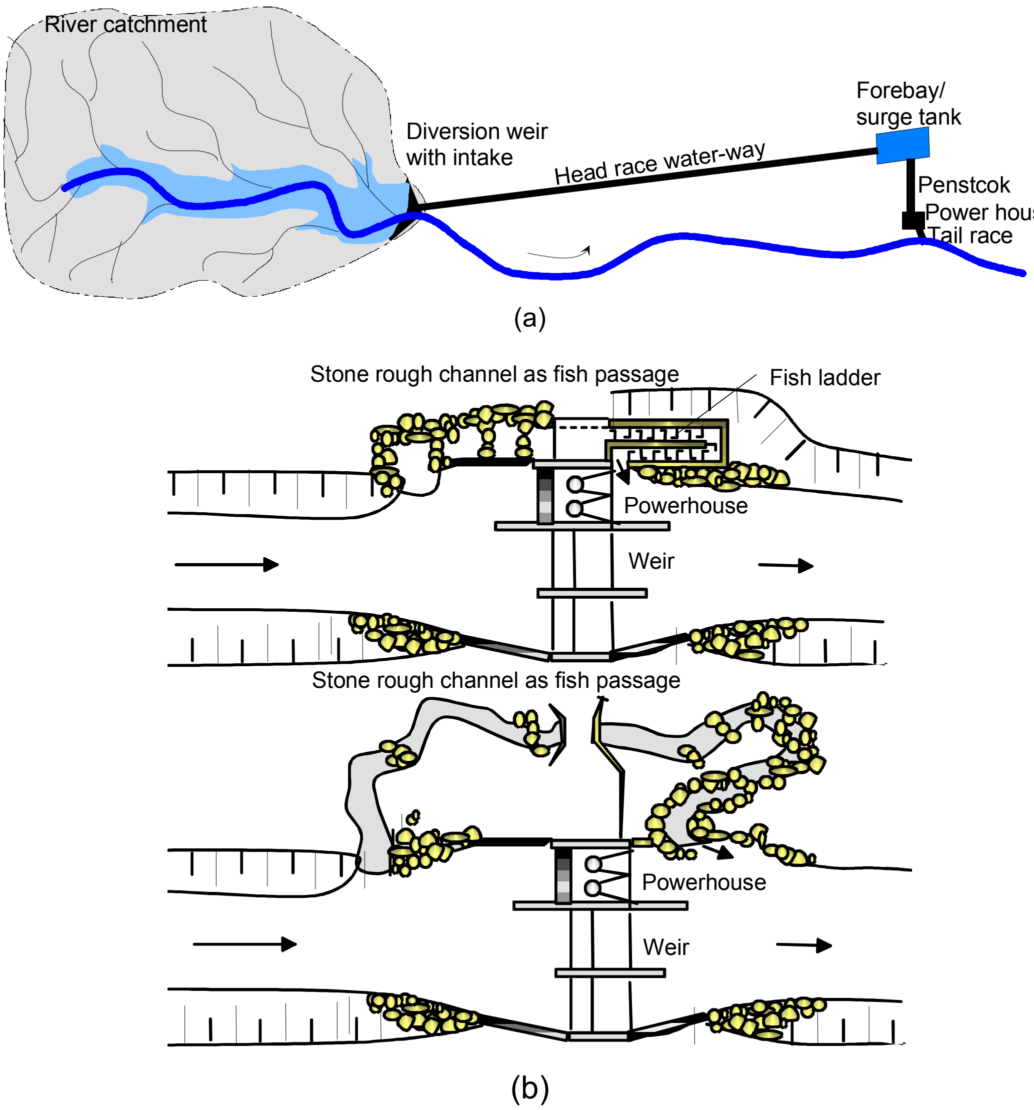


Figure 5.6: Type of small hydropower plants (a) a diversion type high-head, (b) low-head with fish ladder and fish bypass channel [WBW, 1994]

For the simulation of electricity produced by a hydropower plant from water to wire, the following formula modified after Giesecke and Mosonyi (2003) has been used:

$$P_{HP} = \frac{\eta_{Tot} \cdot \rho_W \cdot g \cdot Q_d \cdot h_f \cdot (1 - l_{pel})}{1000} \qquad (5.1)$$

Where,

P_{HP}	Electrical power	$[kW]$
ρ_W	Density of water	$[1000\ kg \cdot m^{-3}]$
g	Acceleration due to gravity	$[9.81\ m \cdot s^{-2}]$
Q_d	Design discharge	$[m^3 \cdot s^{-1}]$
h_f	Design head	$[m]$
$\eta_{Tot} = \eta_T \cdot \eta_{gen} \cdot \eta_{tr}$	Total efficiency	$[-]$
η_T	Turbine efficiency	$[-]$
η_{gen}	Generator efficiency	$[-]$
η_{tr}	Transformer efficiency	$[-]$
l_{pel}	Parasitic electrical losses	$[-]$

In Equation 5.1, the design discharge and head have to be optimised. The design head must be calculated by deducting the total head losses in water conveyance systems and the turbine setting height from the gross head. The gross head is the difference between the upstream and the down stream water levels. To calculate the design head with respect to discharge and power production, some of the following components of a generalized small hydropower plant as shown in Figure 5.7 have been modelled in detail.

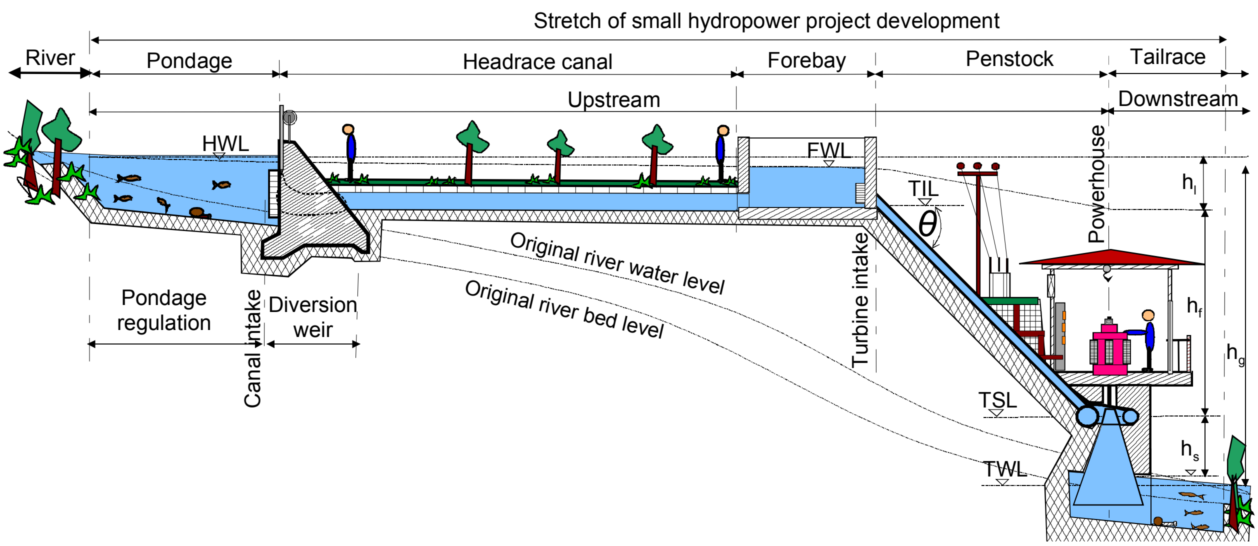


Figure 5.7 Schematic representation of a small hydropower scheme

Since the main objective of this thesis is to develop a model to simulate the design variables for power generation, engineering designs of system components have been omitted. However, some of the data (e.g., penstock size, canal dimensions) as an outcome of simulation process may also be recommended for the design of the some components (such as water channel, penstock etc.) for small hydropower plants at the pre-feasibility level.

In the following sections, a detail description of the hydropower components is presented.

5.3.3.2 Hydrological Parameters

Hydropower plant modelling begins with the input of hydrological data in order to define the design discharge. For this, either a time-series of hydrological data or flow-duration curve data of a river in question is used. Since no water storage is considered in this work, a flow-duration curve method has been adopted. A number of useful commercial computer software is available to process the hydro-meteorological data [e.g, HEC-RAS, HYDRA], and therefore, they have been excluded from the present work.

After the inputting maximum design discharge the computer algorithm (refer Figure 5.8) defines the time-series discharges through turbine. That means that if the river discharge is greater than turbine discharge then the algorithm takes only the turbine discharge. If the river discharge is less than the turbine discharge then the algorithm takes the river discharge.

5.3.3.3 Topographical Parameters

Topographical parameters are necessary for the layout of hydropower components as well as to determine the gross head (refer Figure 5.7). The head water level (HWL), the forebay water level (FWL) and the tail water level (TWL) are specified as input. Similarly, horizontal distances from intake to forebay, from forebay to powerhouse and from powerhouse to tailrace exit must also be specified.

The turbine setting height (h_s) may be positive or negative depending upon the type of turbines selected. In case of reactive turbines (e.g., Francis, Propeller or Kaplan types), h_s is determined through optimisation by checking the cavitations limits. In case of active turbines (Pelton, Turgo and Cross-flow types) the value of h_S is always set above the floodwater elevation.

The developed algorithm, as shown in Figure 5.10, automatically calculates the turbine setting level (TSL).

In order to obtain a reliable value of the net head, which is mainly responsible for the magnitude of the producible power, it is necessary to estimate and calculate, respectively, the head losses along the entire waterway of the hydropower plant.

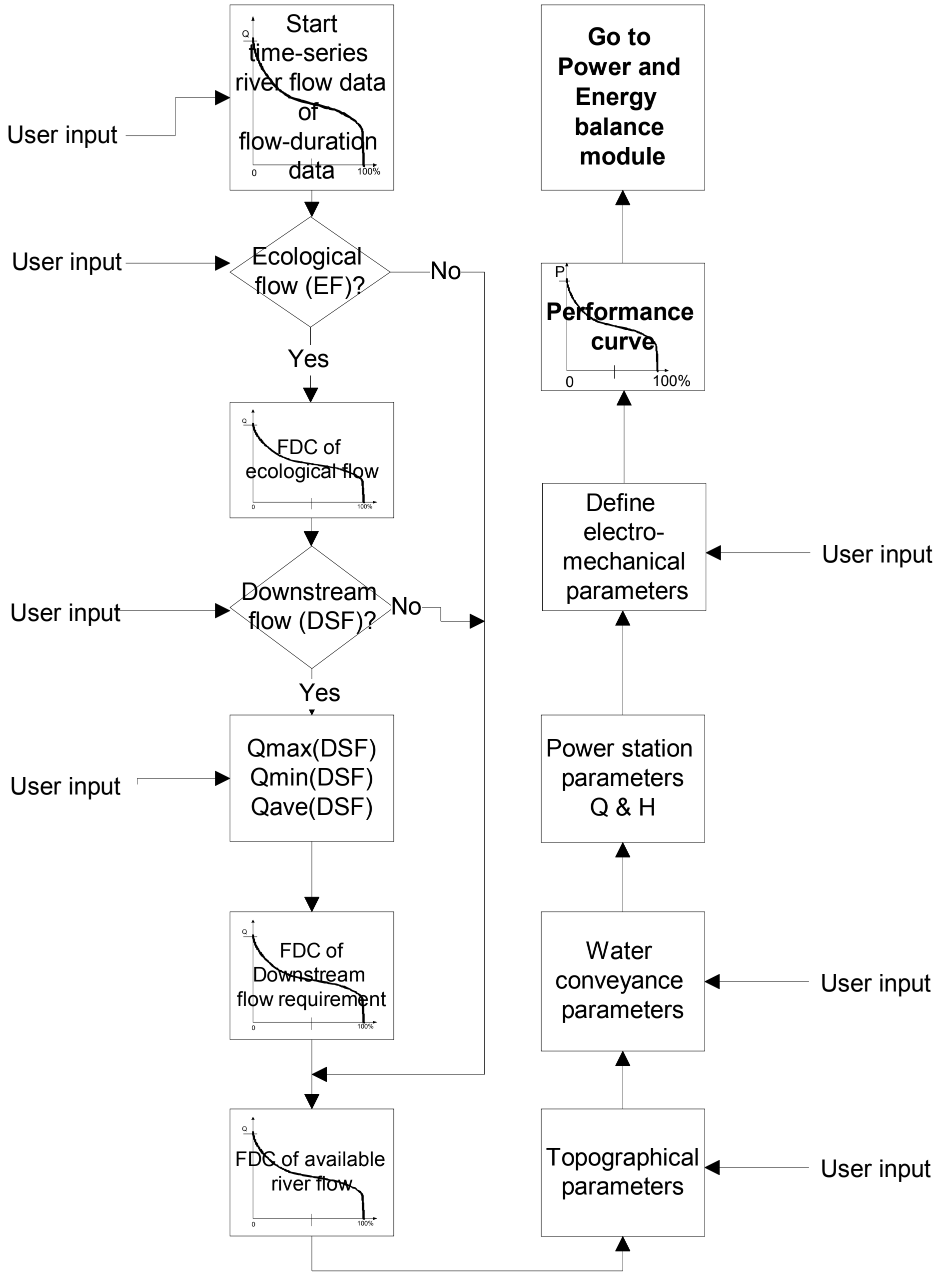


Figure 5.8: General algorithm for hydropower plant module

The word “mainly” refers to the fact that also the efficiency of the turbine(s) and generator(s) reduces the power available for the grid.

The head losses comprise the following partial losses:

- Intake loss, including rack loss
- Friction losses along the entire waterway (canal, tunnel, penstock)
- Local losses along the waterway (bends, valves, etc.)

When the hydropower concept comprises diversion-type plants it is desirable to estimate the head losses along the headwater and/or tailwater canals.

Diversion canals and less frequently tunnels are used as water conveyance from intake to forebay (less frequently surge tanks) in small hydropower projects. They are designed to have uniform cross-section with steady uniform flow (normal flow) so that the energy loss is kept as minimum as possible. To determine the head losses (energy loss) in canals, sections requiring lining or aqueduct must be defined by dividing the canal or tunnel sections in several parts. Moreover, the bends and vertical change in cross-sections as well as the effect of vegetation must also be considered in the canal alignment. This procedure is performed separately using canal design and head loss calculation sub-module.

A detailed calculation of the losses according to the above specifications is possible only, when the layout and general plan of the plant is already at disposal. In other cases, however, the sum of the probable losses can be roughly estimated on the basis of experience.

For calculating the above mentioned head losses several textbooks on applied hydraulics and hydropower development have been published.

Only the head losses at head and tailrace canal sections and penstock are considered in the present work. The developed algorithm then determines the time-series of net head with respect to design discharge. Capacity of a hydropower plant also depends on the proper selection of electrical as well as mechanical equipment. Most important among others are the selection of turbine and generators types.

5.3.3.4 Electro-mechanical Parameters

Using the design head and discharge parameters and the classification criteria given in Table 5.3, the algorithm defines tentatively the type of the power plant. The algorithm then searches the appropriate turbine types, number of machines and number of jets (in case of Pelton and Turgo turbines) to define tentatively the maximum specific speed of the turbine based on design head as suggested by Giesecke and Mosonyi (2003).

With the help of maximum specific speed given in Table 5.5 tentative synchronous speed of generator is determined for each type of turbines.

$$n_T = n_{q,max} \cdot \frac{h_f^{0.75}}{\sqrt{Q_d}} \tag{5.2}$$

Where,

n_T	Tentative speed of generator	[min^{-1}]
$n_{q,max}$	Maximum specific speed of turbine	[min^{-1}]

The algorithm depicted in Figure 5.10 compares and selects the next higher value of synchronous speed for which the number of pair poles is determined. Using this information and the defined frequency of the electrical network, the algorithm calculates the actual synchronous speed of the generator as follows:

$$n = \frac{60 \cdot f}{p} \tag{5.3}$$

Where,

n	Synchronous speed	[min^{-1}]
f	Frequency	Hz
p	Number of pair poles	$[-]$

Sequentially, the actual specific speed of turbine is calculated and required turbine is determined.

$$n_q = n \cdot \frac{\sqrt{Q_d}}{h_f^{0.75}} \tag{5.4}$$

Where,

n	Synchronous speed	[min^{-1}]
n_q	Actual specific speed	[min^{-1}]

Based on net head and design discharge, the algorithm then defines the type of appropriate turbine corresponding to actual specific speed. Consequently, the algorithm determines the runner diameters.

5.3.3.5 Determination of Turbine Efficiency

In practice the turbine efficiencies are provided by the manufacturers and are not readily available at earlier stages of planning process. On the other hand, the relative discharge dependent efficiency of turbine in question is necessary in order to evaluate the performance of the plant on time-series basis. With the help of some empirical formulas (see Appendix I), it is possible to model time-series efficiency for the following four types of turbines at present. These formulas have been modified after RETScreen® to the objective of the present work.

The additional information such as the generator and transformer efficiencies and an allowance for parasitic losses in percentage should also be provided.

5.3.3.6 Time-series Power and Energy Calculation

If a hydropower plant is interconnected with other renewable energy technologies such as wind and photovoltaic power plants then it is important to evaluate the plant performance in short interval (at least in an hourly interval). Therefore, it is necessary to obtain the hourly power value of a hydropower plant. The hydropower plant module has been designed to obtain this hourly time-series power. The algorithm then sums-up the energy produced on an hourly basis to obtain daily energy in kWh.

The time-series power value is then automatically fed into the power simulation module.

5.3.3.7 Model Validation

It is important to validate the model by comparing its performance with respect to existing data obtained either from experiment or published source. To perform this, data published by RETScreen® International under the Minister of Natural Resources Canada (2001-2002) have been used. Table 5.9 summarizes the actual data of the Brown Lake Hydro Project in British Columbia, Canada as well as the data simulated by the present model at 72% of plant capacity for a design discharge of 7.36 m³/s. The efficiency curves of both actual and simulated turbines are compared in Figure 5.9, which shows a fairly acceptable correlation coefficient of $R^2 = 0.63$.

Table 5.3: Summary of manufacturer's data for efficiency comparison

<table>
<tr><th>Description</th><th>Actual</th><th>Model</th><th rowspan="2">Flow (m³/s)</th><th colspan="2">Turbine efficiency</th></tr>
<tr><td>Type of turbine</td><td>Francis</td><td>Francis</td><td>Actual</td><td>Model</td></tr>
<tr><td>Installed capacity (kW)</td><td>6,870</td><td>6,578</td><td>3.50</td><td>0.82</td><td>0.82</td></tr>
<tr><td>Gross head (m)</td><td>109.1</td><td>109.2</td><td>3.85</td><td>0.84</td><td>0.85</td></tr>
<tr><td>Net head (m)</td><td>103.6</td><td>103.6</td><td>4.20</td><td>0.85</td><td>0.87</td></tr>
<tr><td>Turbine diameter (m)</td><td>1.1</td><td>0.86</td><td>4.55</td><td>0.87</td><td>0.89</td></tr>
<tr><td>Penstock diameter (m)</td><td>1.5</td><td>1.5</td><td>4.90</td><td>0.88</td><td>0.90</td></tr>
<tr><td>Synchronous speed for 60 Hz (min^{-1})</td><td>514</td><td>900</td><td>5.25</td><td>0.90</td><td>0.91</td></tr>
<tr><td>Project name:</td><td colspan="2">Brown Lake Hydro Project</td><td>5.60</td><td>0.90</td><td>0.92</td></tr>
<tr><td>Project location:</td><td colspan="2">Approximately 40 km south of Prince Rupert, British Columbia</td><td>5.95</td><td>0.91</td><td>0.92</td></tr>
<tr><td>Project Features:</td><td colspan="2">Connected to BC Hydro at 69 kV</td><td>6.30</td><td>0.92</td><td>0.92</td></tr>
<tr><td>Date commissioned:</td><td colspan="2">December 1996</td><td>6.65</td><td>0.93</td><td>0.92</td></tr>
<tr><td>Turbine manufacturer:</td><td colspan="2">GEC Alsthom (runner by Neyrpic)</td><td>7.00</td><td>0.93</td><td>0.92</td></tr>
<tr><td>Maximum rated capacity:</td><td colspan="2">7,115 kW at 105.6 m net head</td><td>7.35</td><td>0.93</td><td>0.89</td></tr>
</table>

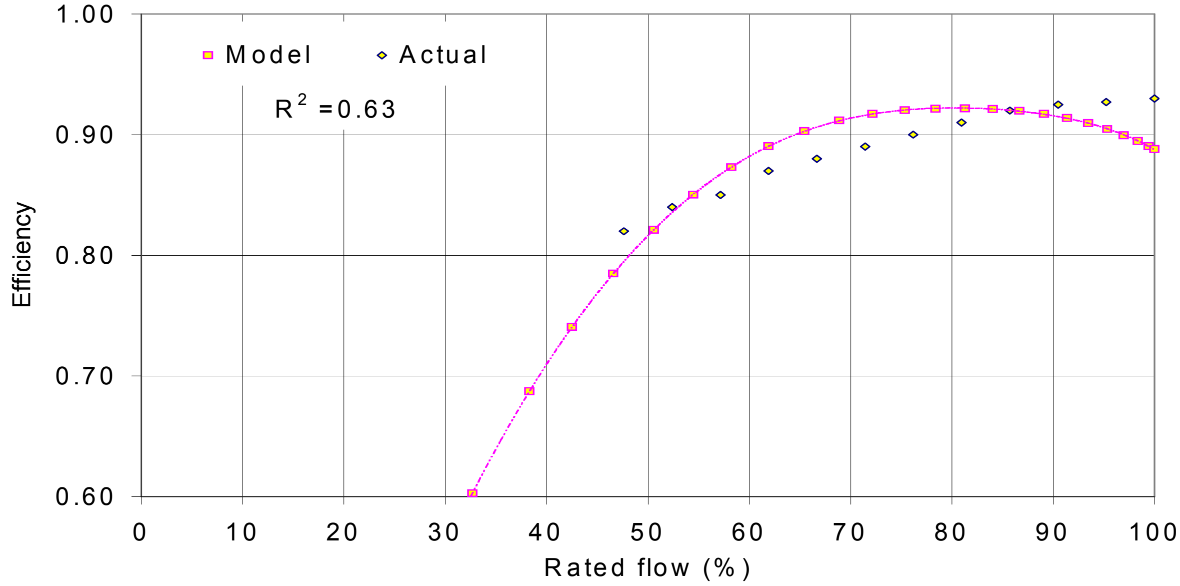


Figure 5.9: Calculated vs. actual turbine efficiency

The 4.3 % discrepancy between the model and the actual installed capacities may be due to the reason that the simulated turbine efficiency for the design discharge is about 4.3 % less than the as-designed manufacturer's turbine efficiency. The best efficiency point lies at 81 % of the design flow.

Further the actual turbine diameter was designed for the horizontal type while the simulated one is for vertical type. Simulated synchronous speed of the generator for 60 Hz frequency has higher rotational speed than the actual one, which according to Equation 5.29, reduces the size of the turbine.

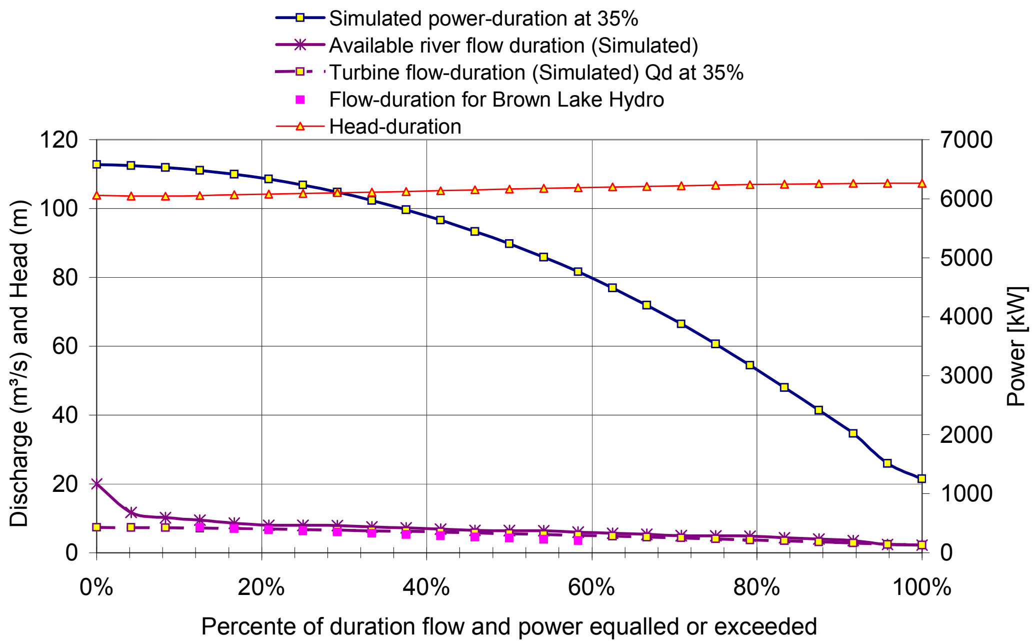


Figure 5.10: The discharge, head and power duration curves at $Q_{d\ 35\ \%}$ simulated by the present model.

Therefore, the outcome of the model may be considered as fairly good for the planning purpose.

Figure 5.10 presents the performance curves plotted for the same project to verify the model's capacity. A discharge-duration of $Q_{d,\ 35\ \%}$ simulated by the model fairly matches with the discharge-duration curve used by the turbine manufacturer for efficiency test as given in Table 5.9. The power and head duration curves for a 72 % plant factor are also shown.

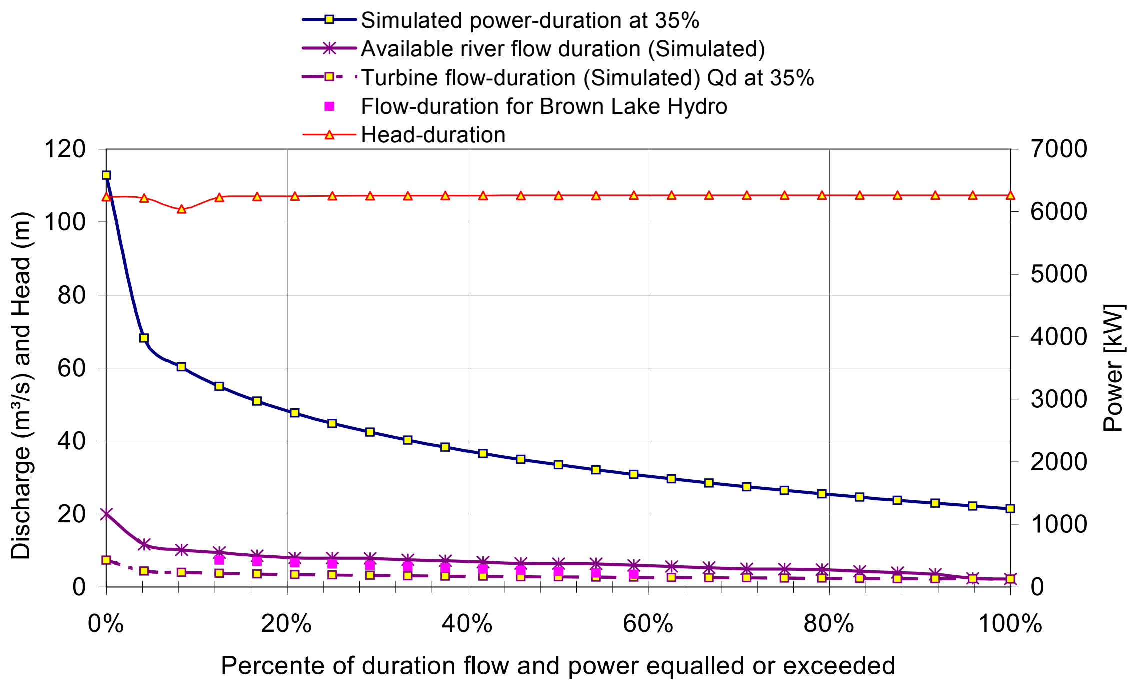


Figure 5.11: The effect of plant factor on plant discharge, head and power duration curves

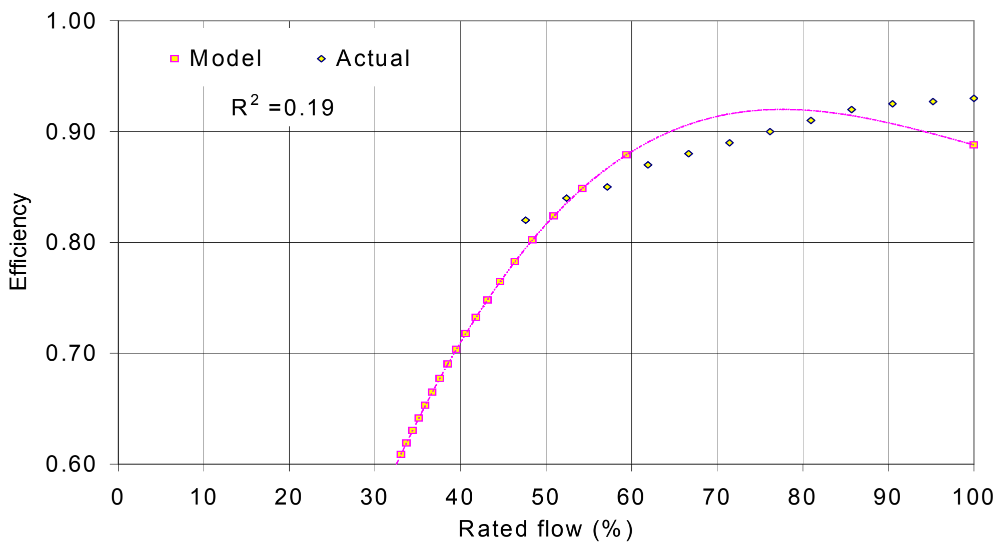


Figure 5.12: Calculated vs. actual turbine efficiency at 40% plant factor

The developed model is also capable for evaluating performance of hydropower plants for various plant factors. This is necessary for the sensitivity analysis of the load dependent power system. Figure 5.11 depicts an example of the effect of 40 % plant factor on the power production as well as the efficiency. As seen in Figure 5.12, the matching with manufacture's efficiency data at this factor is very poor ($R^2 = 0.19$).

5.3.4 Wind Power Plant Module

The power production from a wind turbine is directly proportional to the sweep area of the rotor blades, the cube of the wind velocity (Figure 5.13). It has been found that the optimum air mass balance occurs when the leeward wind velocity is equal to one third of the luv-ward wind velocity. That means not all of the kinetic energy of blowing wind can be utilized.

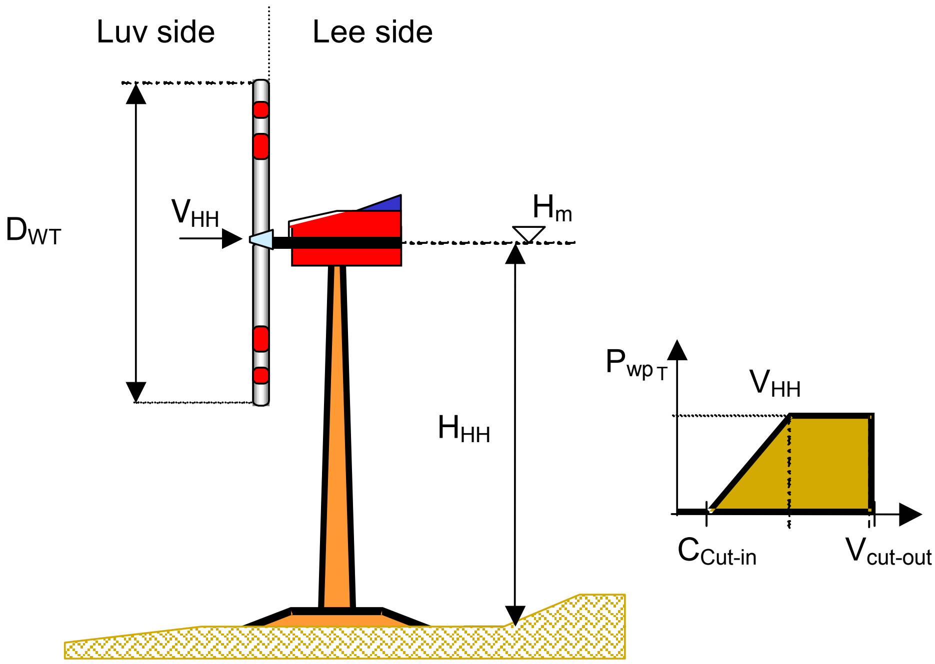


Figure 5.13: A wind power plant with power characteristics

The ratio of wind power drawn by a rotor to the theoretical wind power is called the performance coefficient or popularly known as the Betz coefficient. This coefficient shows that only about 60% the rotor can utilize the theoretical wind power. Taking into consideration the efficiency of turbine, gears, and generator the wind power plant module is designed using the following formula:

$$P_{WP} = 0.5 \cdot C_P \cdot \eta_{Tot} \cdot \rho_a \cdot \frac{\pi \cdot D_{WT}^2}{4} \cdot \bar{v}_{HH}^3 \tag{5.5}$$

Where,

P_{WP}	Electrical power	$[W]$
ρ_a	Air density	$[kg \cdot m^{-3}]$
$\eta_{Tot} = \eta_t \cdot \eta_g \cdot \eta_G \cdot \eta_{tr}$	Total efficiency	$[-]$
C_P	Betz coefficient = 0.59	$[-]$
η_{tr}	Transformer efficiency	$[-]$
η_G	Gear efficiency	$[-]$
η_t	Rotor efficiency	$[-]$
η_g	Generator efficiency	$[-]$
D_{WT}	Rotor diameter	$[m]$
$\bar{v}_{HH}$	Velocity of air at hub height	$[m \cdot s^{-1}]$

Long-term time series wind-velocity data are not readily available. To predict this, it is suggested to measure short-term wind data at the site in question and compare it with a nearby site having long-term wind data. This is known as ‘measure, correlate and predict’ technique [Patel, 1999]. The Weibull probability distribution function is popular in predicting wind characteristics defined mainly by three parameters: (a) long-term mean wind speed, (b) scale factor and (c) shape factors.

To simulate a wind power plant it is necessary to input the following data:

Site parameters:

- Site elevation
- Air density at sea level
- Turbine hub height
- Anemometer height
- Scale factor
- Shape factor

Manufacturer’s parameters:

- Type of wind turbine
- Cut-in velocity
- Cut-out velocity
- Turbine efficiency
- Generator efficiency
- Turbine diameter

The scale and shape factors are used to determine the rated wind velocity that is necessary to develop a velocity-power curve.

Air density varies with air temperature and pressure and therefore varies with the altitude. The combined effect of these factors must be taken into account in order to find the site-specific air density.

The wind velocity increases with the increase in height from the earth's surface and is also affected by the site terrain. Therefore, wind turbine's hub is located higher than mounting height of the wind velocity-measuring instrument (anemometer).

The algorithm for wind power module is presented in Figure 5.14.

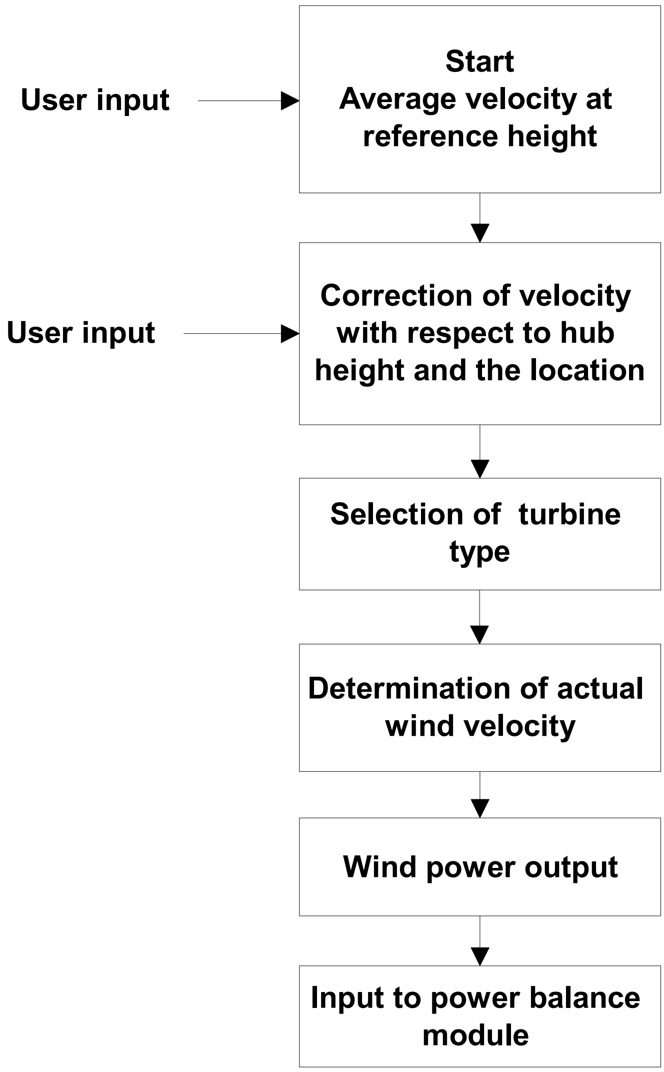


Figure 5.14: General algorithm for wind power module

5.3.5 Photovoltaic Plant Module

The electrical power from a photovoltaic cell depends on the radiation flow of sun's rays on that cell

$$P_{PV} = \eta \Phi \tag{5.6}$$

Where,

P_{PV}	Electrical power from photovoltaic cell	$[W]$
η	Efficiency of the cell	$[-]$
Φ	Radiation flow of solar light	$[W]$

The radiation flow of sun's rays on a horizontal surface of a photovoltaic cell is found using the following relationship:

$$\Phi = S \cdot A_S \cdot \cos\theta_{gen} \tag{5.7}$$

Where,

S	Solar irradiance	$[W \cdot m^{-2}]$
A_S	Surface area of a photovoltaic cell	$[m^2]$
θ_{gen}	Angle of incidence of sun's rays to photovoltaic cell	$[degree]$

The angle of incidence on horizontal plane is the angle between incoming sunlight and a line normal to the plane (see Figure 5.15).

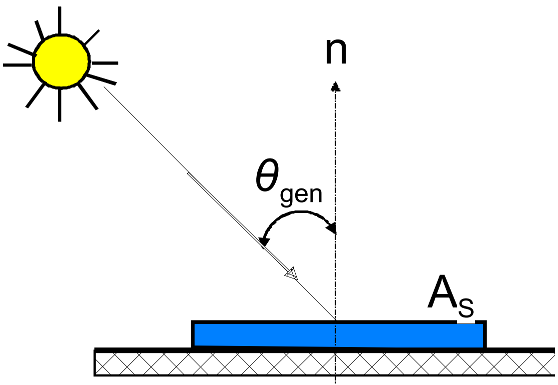


Figure 5.15: Angle of incidence on horizontal plane of a photovoltaic module

To optimise the power output from a photovoltaic plant, it is thus required to define the angle of incidence of sunlight at any site using following information:

1. Orientation of the surface of the plant with respect to sun's rays
2. Definition of geographical location of the site (Latitude, date and time)
3. Determination of global solar irradiation

The angle of incidence on a tilted plane is a complex combination of the following 5 different angles, which is found from trigonometry (refer Figure 16):

$$\begin{aligned}\cos\theta = {} & \sin\delta\cdot\sin\varphi\cdot\cos\gamma_E - \sin\delta\cdot\cos\varphi\cdot\sin\gamma_E\cdot\cos\alpha_E \\ & + \cos\delta\cdot\cos\varphi\cdot\cos\gamma_E\cdot\cos\omega + \cos\delta\cdot\sin\varphi\cdot\sin\gamma_E\cdot\cos\alpha_E\cos\omega \\ & + \cos\delta\cdot\sin\gamma_E\sin\alpha_E\cdot\sin\omega\end{aligned} \tag{5.8}$$

Where,

δ	Declination angle	[degree]
ω	Solar hour angle (before noon: positive, after noon: negative)	[degree]
φ	Latitude (North: positive, south: negative)	[degree]
γ_{PV}	Tilt angle of the surface of the photovoltaic panels	[degree]
α_{PV}	Azimuth angle of the panels with respect to meridian	[degree]

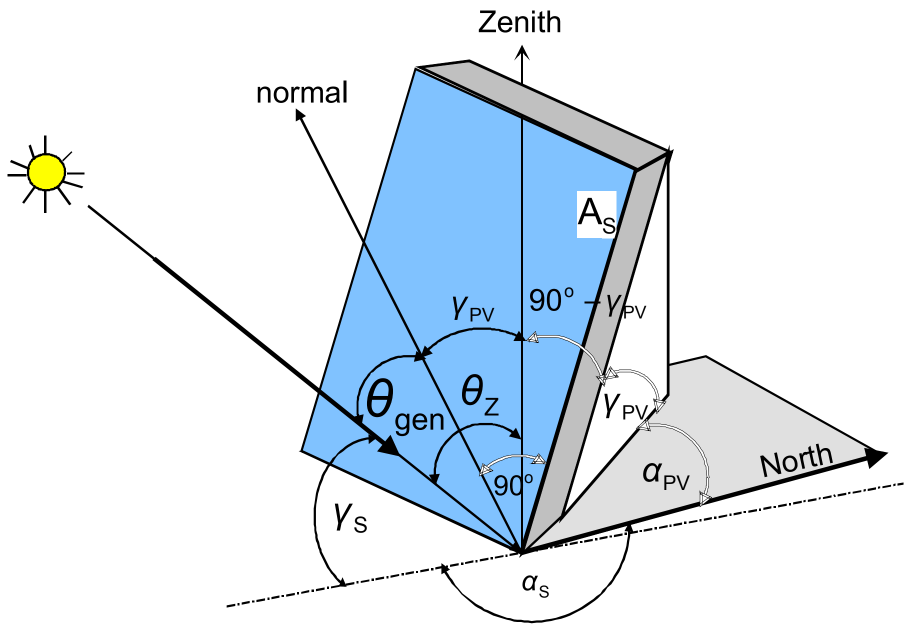


Figure 5.16: Definition of angles for tilted surface of photovoltaic plant with respect to sunrays [after Quaschning, 2003].

Detail description of these angles, geographical location of a site and information on global solar radiation found in specialized literature [Khartchenko, 1995; Duffie and Beckman, 1991; Quaschning, 2003 etc.] are presented in Appendix I for easy reference

The developed algorithm is summarized in Figure 5.17.

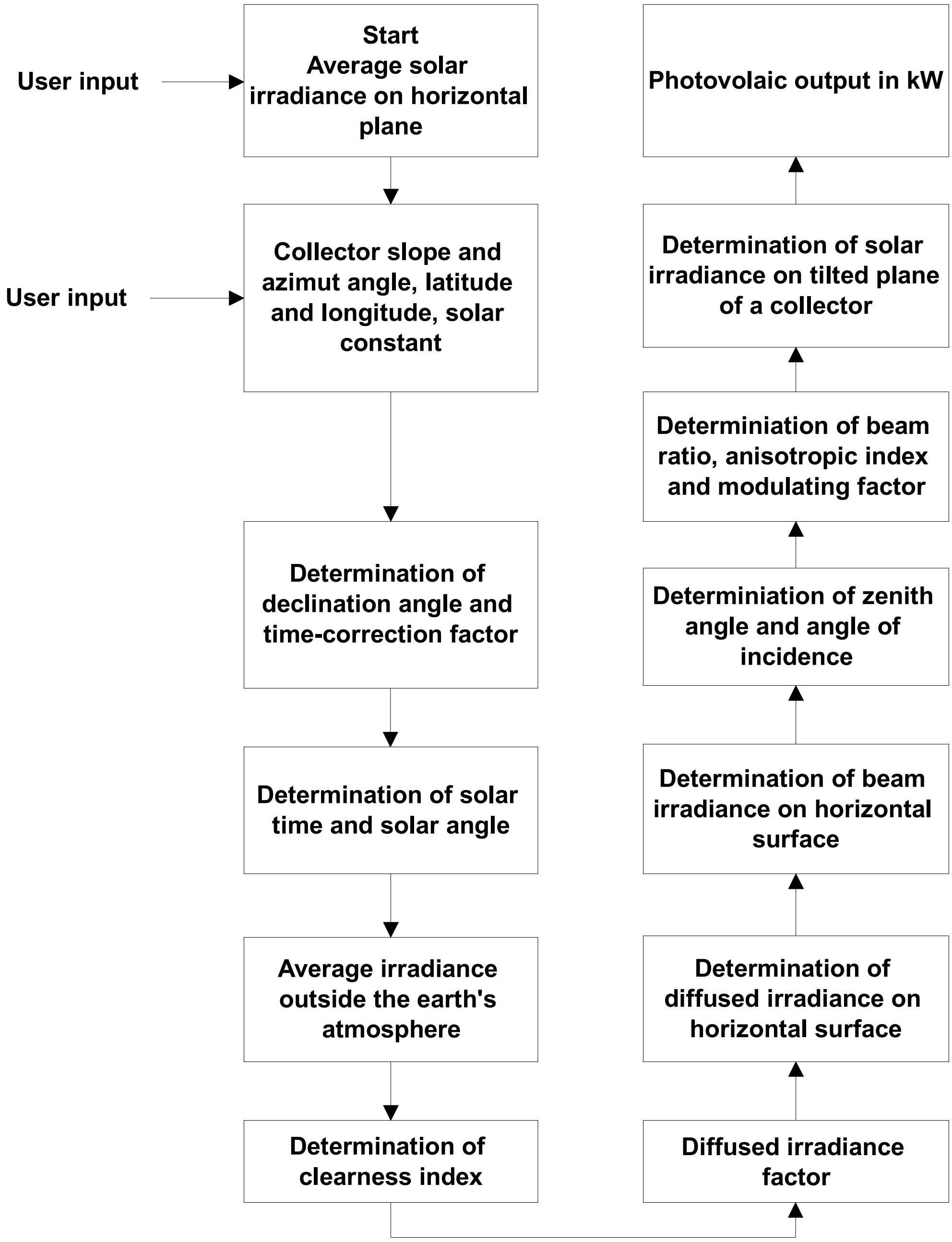


Figure 5.17: General algorithm for photovoltaic plant module

5.3.6 Mini-grid Module

5.3.6.1 Basics

A decentralized power system, as conceived in this work, may consist of one or several power sources (generators) and one or more power sinkers (loads) connected to the same electrical power grid.

Figure 5.18 summarizes the various types of power grid, which are also applicable for both central and isolated power systems.

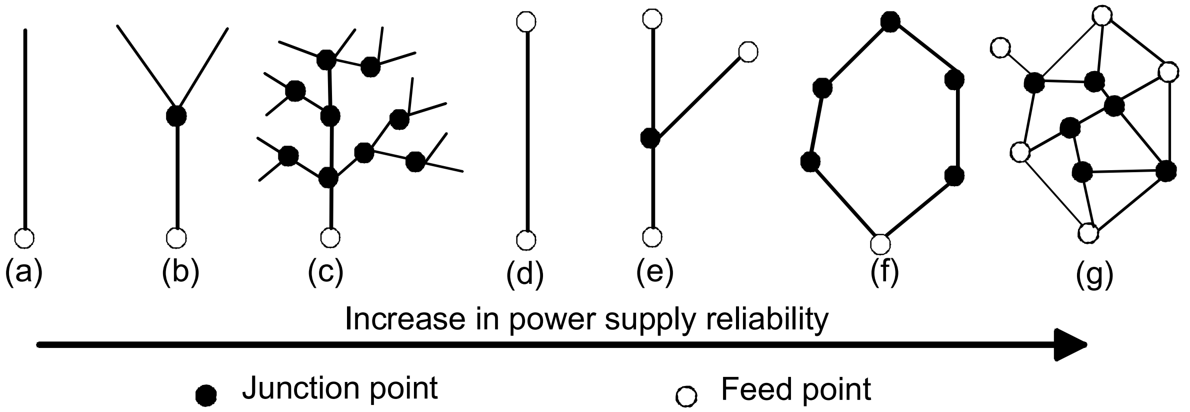


Figure 5.18: Basic types of power grids a) on one side fed power line, b) & c) on one side fed branched lines, d) on two sides fed line, e) more than two sides fed branched lines, f) one side fed ring circuit, g) meshed grid with several feeder [After Flosdorff und Hilgarth, 2000].

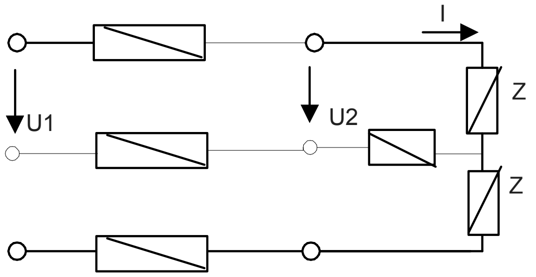
The power supply reliability of grid schemes type (f) and (g) is high but the cost of implementation and operation is also high. Therefore, for a small decentralized power system the grid scheme type (e) is modelled in this work. Modelling of scheme type (f) and (g) has been omitted at present. It is to be noted here however that, with some modification, this model may also be used for simulating all the above grid types.

For the simulation of a load dependent isolated power system it is necessary to model the system as a whole i.e., in combination of generating, transmitting and distribution. At present the mini-grid module is limited to the computation of nodal voltage drops and active power flows in the lines between the nodes. With three-phase alternating current lines a symmetrical load is always presupposed, so that in each case only single-phase needs to be counted [Flosdorf and Hilgarth, 2000]. Thus three-phase alternating current and single-phase alternating current mains may be treated in the same way.

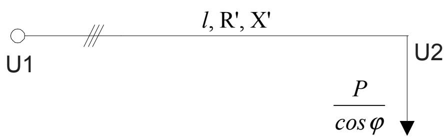
The decentralized power system that is being considered in this work falls under the category of low and medium voltage transmission grids having maximum capacity and length below 60 kV and 30 km respectively. Inversin (2000) argues for simple form of mini-grid for remote regions of developing countries and provides detailed guidelines for design of single source mini-grid. The present work is dedicated to design a mini-grid with multiple supplier and consumer with a certain degree of electro-technical standard. Therefore, complex calculation processes can be avoided using the following assumption:

- The three-phase alternating current transmission line can be assumed as three single-phase alternating current,

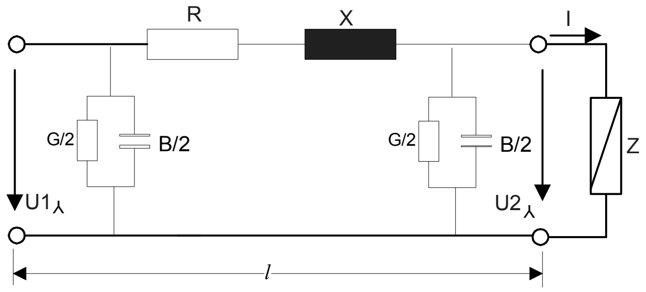
- The transmission circuit shown in Figure 5.19 a can be presented symbolically through an arrow line with an active power and power factor (see Figure 5.19 b).
- Further, below 60 kV the capacitive effect between transmission lines and ground (see Figure 5.19 c) can be neglected [Widmer and Arter, 1992].
- Finally, a transmission line can be simply described through an equivalent circuit by its resistance and inductance (see Figure 5.19 d).



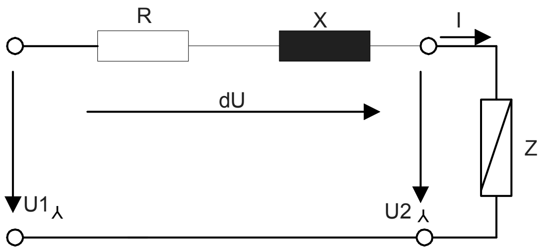
(a) Three phase line circuit



(b) Single line representation of three-phase transmission line with consumer



(c) Equivalent circuit of a transmission line with concentrated resistances R, X and conductivity G, B.



(d) Simplified equivalent circuit of a transmission line with consumer.

Figure 5.19: Equivalent circuit diagrams used to model the decentralized power grid.

The modeling mini-grid is explained using the equivalent electrical diagram as shown in Figure 5.19 d.

Simulation of a mini-grid consists of determining the power flow from one node to another and the voltage drop at the nodes as shown in Figure 5.20.

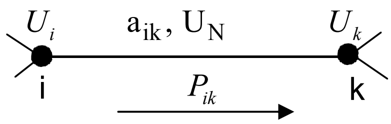


Figure 5.20: Schema for node-to-node power exchange

The power flow from ith-node to kth-node may be described as

$$P_{ik} = (U_i - U_k) \cdot U_N \cdot a_{ik} \tag{5.9}$$

If $U_k > U_i$, then the power P_{ik} has a negative value. In this case the power flows from node k to i. The process of determining unknown power flow in line stretches of a grid through known node voltages and known admittance is known as node-potential process [Flosdorf and Hilgarth, 2000]. These voltages are first determined utilizing Kirchhoff's node laws as shown in Figure 5.21.

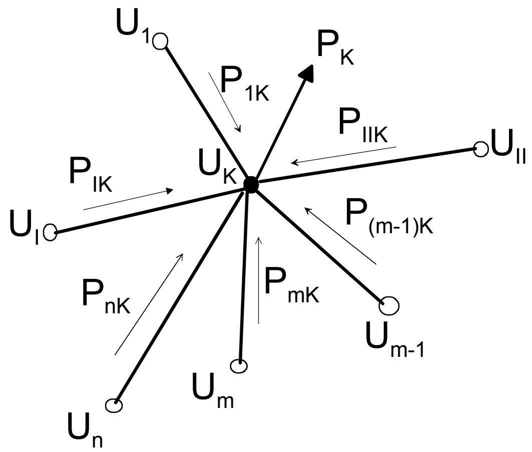


Figure 5.21: Power flow in a node

$$\sum_{j=1}^{n} P_{jk} + \sum_{i=1}^{m} P_{ik} - P_k = 0 \tag{5.10}$$

Finally, the node voltage U_k:

$$U_k = \frac{\sum_{i=1}^{m} U_i \cdot a_{ik} - \left(\frac{P_k}{U_N} \right)}{\sum_{i=1}^{m} a_{ik}} \tag{5.11}$$

5.3.6.2 The Node-Potential Method for Power Flow Calculation

The node-potential method is used to determine the necessary conductor sizes and voltage drops. This method is also useful for determining direct and single phase alternating current if U_N is replaced through $U_N/2$. Considering the following assumptions, a general node-potential process of a mini-grid as shown in Figure 5.22 has been described hereunder [Folsdorf and Hilgarth, 2000]:

- Only the symmetrically loaded alternating current network will be determined.

- All phase angles in the network are considered approximately the same.
- The power factors of all connected consumers are considered to be nearly the same.
- Off-take nodes are the junctions, where at least three line conductors are connected together. In addition to this all points at which consumers are connected are also considered as nodes. Node voltages are marked as $U_1, U_2, \ldots$.
- Feed points are intake nodes, at which for the computation the line-to-line voltage is known. Intake nodes into which generators feed are understood as off-take nodes with powers having negative sign. Feed point voltages are denoted through $U_I, U_{II}, \ldots$.

The mini-grid considered for a hypothetical rural electrification in Nepal (refer Figure 7.2 in Chapter 7) consists of 5 intake nodes and 9 off-take nodes as shown in Figure 5.22.

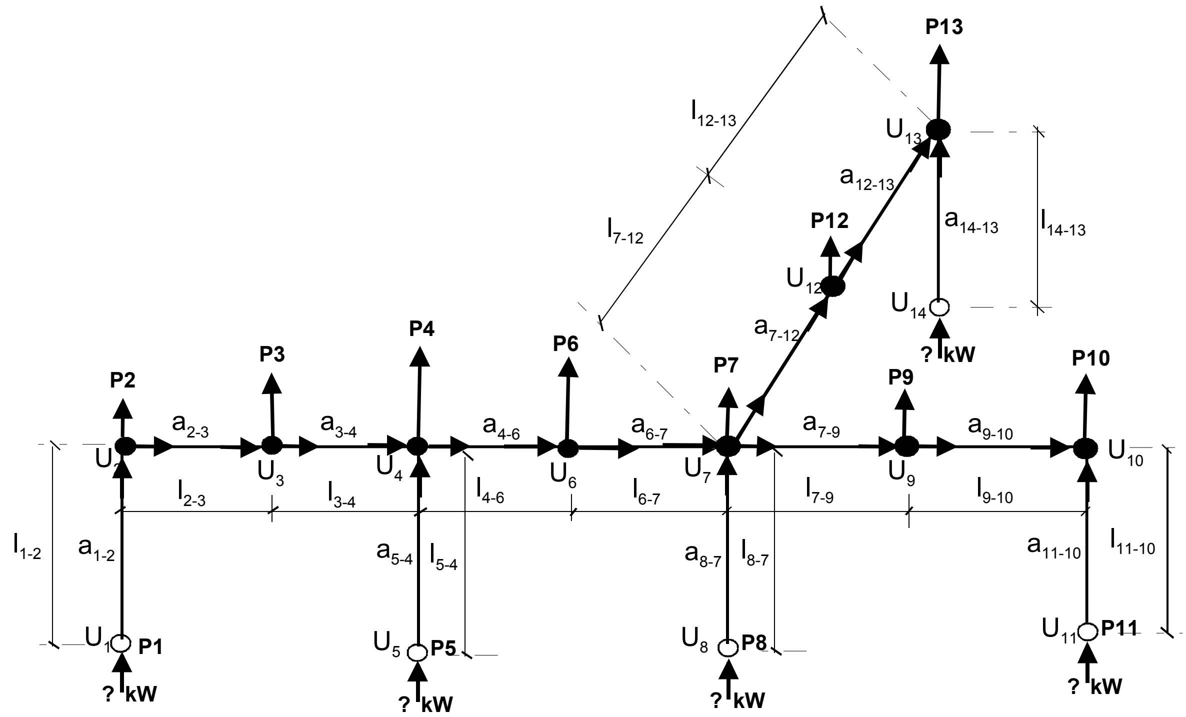


Figure 5.22: Decentralized power system of a village in Nepal

Arrows show the power flows at these nodes. Because this is a case of an isolated mini-grid, i.e., it is not interconnected with regional grid; it has no feed points as such. Therefore, $U_I, U_{II}, \ldots$ are set to zero. The reference voltage is the grid voltage U_N, which is subject to optimisation.

Using Figure 5.20 and Equation 5.10, the node-potential process for the current flow in the conductor from i^{th}-node to k^{th}-node can be expressed through a matrix of admittance of the conductor and the vector of unknown voltage drop between these nodes.

$$[I_{ik}] = [a_{ik}] \cdot [U] \qquad (5.12)$$

Where,

I_{ik}	Current flow from i[th]-node to k[th]-node ($i \neq k = 1,2,3 \ldots n$)	[A]
a_{ik}	Conductor's admittance between k[th]-node to k[th]-node	[S]
U	Node voltage	[V]
n	Number of nodes	[–]

Referring to the electrical equivalent circuit shown in Figure 5.26 d, the admittance of line conductors can then be written as:

$$a_{ik} = \frac{1}{l_{ik} \cdot (R_{l,ik} + X_{l,ik} \cdot \tan\varphi)} \qquad (5.13)$$

Where,

l_{ij}	Length of equivalent conductor	[km]
$R_{L,ik}$	Ohmic part of the line impedance	$[\Omega \cdot km^{-1}]$
$X_{L,ik}$	Inductive part of impedance	$[\Omega \cdot km^{-1}]$

Referring to Equation 5.69 altogether 13 power flow equations can be written:

1 $P_{1-2} = (U_1 - U_2) \cdot U_N \cdot a_{1-2}$

2 $P_{2-3} = (U_2 - U_3) \cdot U_N \cdot a_{2-3}$

3 $P_{3-4} = (U_3 - U_4) \cdot U_N \cdot a_{3-4}$

4 $P_{5-4} = (U_5 - U_4) \cdot U_N \cdot a_{5-4}$

5 $P_{4-6} = (U_4 - U_6) \cdot U_N \cdot a_{4-6}$

6 $P_{6-7} = (U_6 - U_7) \cdot U_N \cdot a_{6-7}$

7 $P_{8-7} = (U_8 - U_7) \cdot U_N \cdot a_{8-7}$

8 $P_{7-9} = (U_7 - U_9) \cdot U_N \cdot a_{7-9}$

9 $P_{9-10} = (U_9 - U_{10}) \cdot U_N \cdot a_{9-10}$

10 $P_{11-10} = (U_{11} - U_{10}) \cdot U_N \cdot a_{11-10}$

11 $P_{10-11} = (U_{10} - U_{11}) \cdot U_N \cdot a_{10-11}$

12 $P_{12-13} = (U_{12} - U_{13}) \cdot U_N \cdot a_{12-13}$

13 $P_{14-13} = (U_{14} - U_{13}) \cdot U_N \cdot a_{14-13}$

Using Equation 5.70 the power balance equations at each node follow:

$$(a_{1-2})U_1 - a_{1-2}U_2 = -\frac{-P_1}{U_N}$$

$$-a_{1-2}U_1 + (a_{1-2} + a_{2-3})U_2 - a_{2-3}U_3 = -\frac{P_2}{U_N}$$

$$-a_{2-3}U_2 + (a_{2-3} + a_{3-4})U_3 - a_{3-4}U_3 = -\frac{P_3}{U_N}$$

$$-a_{3-4}U_3 + (a_{3-4} + a_{5-4} + a_{5-6})U_4 - a_{5-4}U_5 - a_{4-6}U_6 = -\frac{P_4}{U_N}$$

$$-a_{5-4}U_4 + (a_{5-4})U_5 = -\frac{-P_5}{U_N}$$

$$-a_{4-6}U_4 + (a_{4-6} + a_{6-7})U_6 - a_{6-7}U_7 = -\frac{P_6}{U_N}$$

$$-a_{6-7}U_6 + (a_{6-7} + a_{8-7} + a_{7-9} + a_{7-12})U_7 - a_{8-7}U_8 - a_{7-9}U_9 - a_{7-12}U_{12} = -\frac{P_7}{U_N}$$

$$-a_{8-7}U_7 + (a_{8-7})U_8 = -\frac{-P_8}{U_N}$$

$$-a_{7-9}U_7 + (a_{7-9} + a_{9-10})U_9 - a_{9-10}U_{10} = -\frac{P_9}{U_N}$$

$$-a_{9-10}U_9 + (a_{9-10} + a_{11-10})U_{10} - a_{11-10}U_{11} = -\frac{P_{10}}{U_N}$$

$$-a_{11-10}U_{10} + (a_{11-10})U_{11} = -\frac{-P_{11}}{U_N}$$

$$-a_{7-12}U_7 + (a_{7-12} + a_{12-13})U_{12} - a_{12-13}U_{13} = -\frac{P_{12}}{U_N}$$

$$-a_{12-13}U_{12} + (a_{12-13} + a_{14-13})U_{13} - a_{14-13}U_{14} = -\frac{P_{13}}{U_N}$$

$$-a_{14-13}U_{13} + (a_{14-13})U_{14} = -\frac{-P_{14}}{U_N}$$

After arranging the above equations in the matrix form according to 5.13, it will be noticed that the coefficients (admittance) of the node-point potentials make a symmetric matrix (It is shown in Figure 5.23 partially due to space constraints).

Node	1	2	3	4	⋮
1	a_{1-2}	$-a_{1-2}$	0	0	0
2	$-a_{1-2}$	$a_{1-2}+a_{2-3}$	$-a_{2-3}$	0	0
3	0	$-a_{2-3}$	$a_{2-3}+a_{3-4}$	$-a_{3-4}$	0
4	0	0	$-a_{3-4}$	$a_{3-4}+a_{5-4}+a_{5-6}$	⋮
⋮	0	0	0	⋮	⋮

Figure 5.23: A sample node-admittance matrix

The main diagonal shows the total admittances of each grid branch merging into the same node. It characterises the connection of a node with another node in a grid. This matrix is known as node-admittance matrix [Flosdorff and Hilgarth, 2000]. The elements outside the main diagonal always consist of negative admittances of those line stretches that directly connect a node with neighbourhood nodes.

The matrix is symmetric because the cross-point of, as an example, the 3rd column of the 2nd row has the same admittance as the 2nd column of the 3rd row. There exist no direct connections between the nodes 1-3; 1-4; 2-4.

Therefore the admittances are set to zero. This generality of node-potential method is applicable to any type of grid (see Figure 5.18).

The solution of matrix (refer Figure 5.23 can be found using either the Newton-Raphson method or Gaussian elimination method, the description of which may be found in any standard book of mathematics. At present the Gaussian elimination method has been used. A complete module of mini-grid has been presented in Appendix (II).

During the calculation of electrical supply lines and networks it is aimed at that an energy transfer from the producer to the consumer is as economic as possible. The transmission voltage and cross-section of conductors are selected in order to transmit the power safely to its consumers. The voltage differences between the nodes are to be held within the permissible limits (< 5 %). The maximum acceptable current loads of the transmission is meant for normal operation and short-circuit is kept so that inadmissible heating of the conductor is avoided.

6 POWER SYSTEM SIMULATION AND OPTIMIZATION MODEL

6.1 Power System Simulation Model

6.1.1 General

As mentioned in Chapter 2, to analyse the power and energy balance within each time-step of an electric power system based on renewable energy sources essentially needs time-series simulation method. The power system simulation module, as shown in Figure 6.1, may consist of the following main components:

- Primary and auxiliary power generators
- Mini-grid
- Energy storage with balance of system devices, and
- Primary and deferrable loads

The present power system module includes several small hydropower plants having capacity up to 10 MW, one photovoltaic power plant and one wind power plant, an energy storage device (a battery bank) and several loads. The power generators are named here as primary generators.

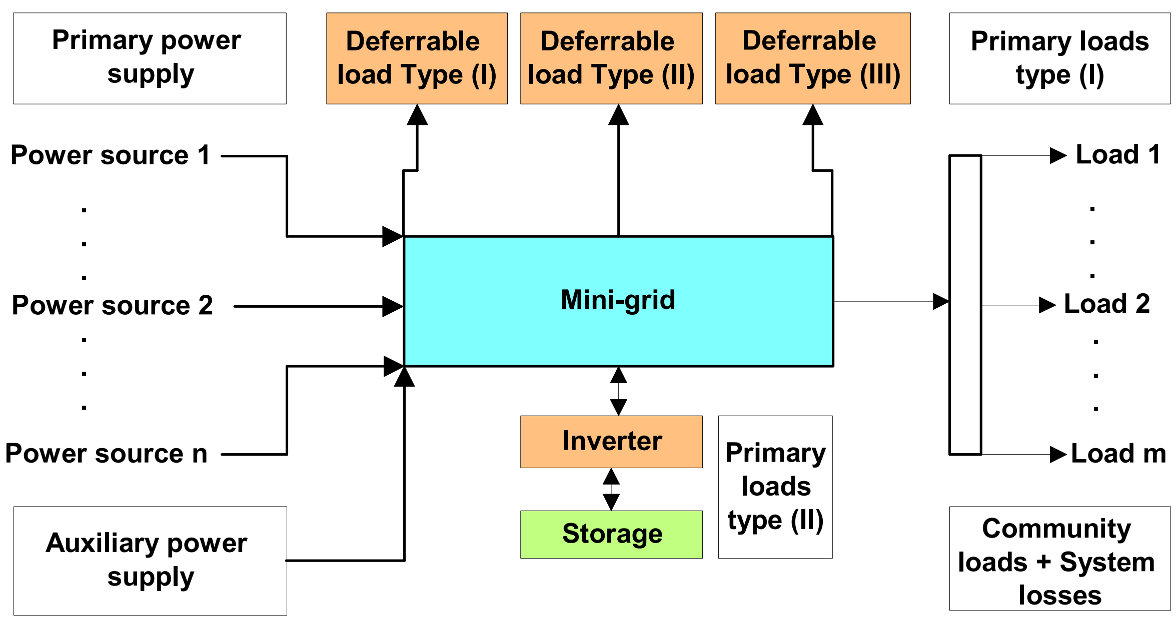


Figure 6.1: Schematic of power and energy balance

The primary power generators and mini-grid have been discussed in Chapter 5. The auxiliary power generators may be fuel-fired (e.g., as diesel or biomass) thermal power generators. They may be modelled and added separately. The discussion over these generators is out of objectives of the present work. In the following paragraphs the primary and deferrable loads are classified.

These loads form an important component of a decentralized power system in order to increase the technical as well as economical efficiencies and therefore are defined hereunder thoroughly.

6.2.2 Classification of Loads

The loads of a decentralized power system as modelled here are divided into primary and deferrable loads.

Primary loads: Primary loads are the main loads of the system. They consist of the electrical loads for lighting, heating and motors demanded by the community as well as self-consumption of the power plants. There are two categories of primary loads considered in this work. The **primary loads type (I)** is the main load, which must be covered by the generating plants and energy storage facilities at any time. These loads must be satisfied with priority (refer section 3.2). Moreover, the network power loss and other parasitic losses also fall in this category. The economic characteristics of primary loads have been discussed in Chapter 3 (refer Figure 3.1).

The **primary loads type (II)**, on the other hand, is that load, which is primarily meant for storing excess (secondary) energy (e.g. a battery bank) during low load periods. Doing so increases the load factor of the system and hence increases the economic efficiency (refer Figure 3.8 in Chapter 3). In the present power system, where the installed capacities of primary power generators are selected below the maximum system load, the energy stored in the battery bank is automatically used to meet the energy deficit of the system (see Figure 6.2). Hence, the battery bank will be called as secondary power generator

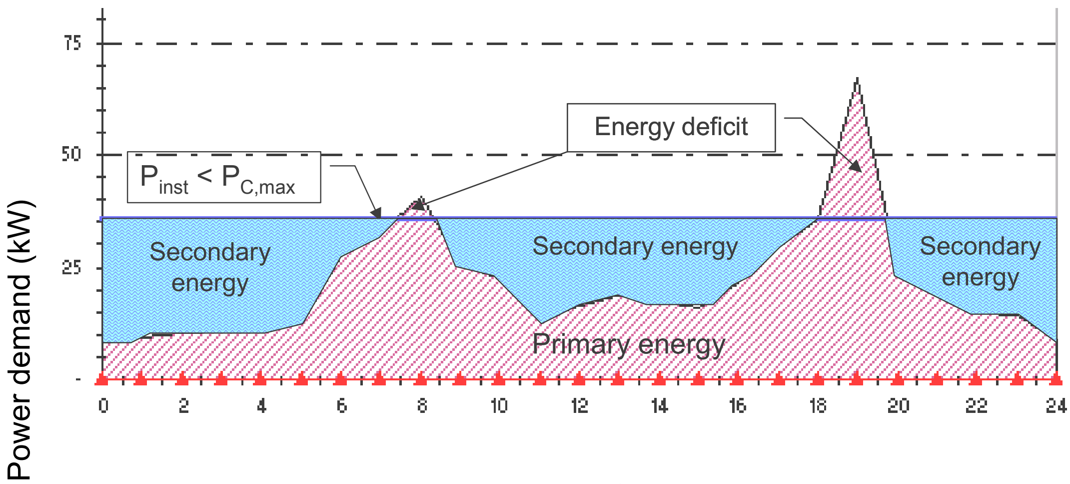


Figure 6.2: Definition of primary and secondary energy of a system demand curve

It is permanently connected to the power system via charging and discharging device known as the inverter (see Figure 6.1). Since the battery bank and the inverter have their own efficiency, a certain amount of energy is lost during the charging and discharging process. This loss must be added to the system demand as primary load type (I) in order to determine the optimum size of the battery bank.

Since the energy is consumed and delivered within the system, the primary load type (II) has only indirect influence in the economic efficiency.

If the primary power generators have enough capacity to meet both the primary load types (I) & (II), then the battery bank should automatically be switched off after fully charged. Any excess power and energy must then be balanced via deferrable loads.

Deferrable loads: Deferrable loads are those loads which could be connected selectively in order to utilize the excess power and energy available after satisfying the need of the primary loads type (I) and (II). That means these loads are connected only when there is a desire to use secondary power and energy available in the system. Hence the power system needs some sort of control mechanisms, which is popularly known as supervisory control [Manwell et al, 1998]. There are three types of deferrable loads modelled at present.

Deferrable load type (I) and (II) are loads that could be utilized for the additional benefit to the system. In this work **deferrable load type (I)** is meant for charging batteries for those consumers who are living beyond the mini-grid reach. These batteries do not give energy back to the system. It utilizes exclusively the excess active power and energy. Hence it serves as an additional load to the system. The **deferrable load type (II**) is the load, which consumes both active and reactive power and energy. The devices such as water pumps for drinking water or irrigation, motors utilized for grinding cereals, water boilers, rice cookers and other mechanical power tools etc. may fall in this category of loads. They are also known as end-use devices. Therefore, these loads should be used categorically during the off-peak hours.

The concept of end-use devices has been introduced in practice in order to increase the system performance of a stand-alone hydropower plant for rural electrification in developing countries. Rural electricity consumers (RECs) have been encouraged to own and utilize end-use devices during the off-peak hours. The problems of such concept and its way-out have been discussed in Chapter 1.

The idea to use deferrable loads centrally by the rural electricity entrepreneur (REEs) has the following two main advantages: firstly, the consumers have no burden at all of utilizing end-use devices. They are free for other useful works during the off-peak hours. For example, RECs may also have important agricultural or other social activities during the daytime off-peak hours rather than making sure for using end-use devices in order to increase the load factor. During the night-time off-peak hours they do not have to worry about and may have rest. Secondly, the REEs will have good control over the utilization of these devices so that they can optimally and reliably run the power system. The disadvantage of increased cost and operation complexity will be compensated by the good use of this excess energy for earning additional money. Therefore, this type of loads may be added to the primary load type (I) and name here together as potentially saleable load (refer section 3.2). The economic effect of which is the subject of the sensitivity analysis.

Deferrable load type (III) for mini-grid is optional and may be designed to ‘flatten’ the load curve. It is used to consume completely the excess energy that is available after satisfying all the demand imposed by the primary and deferrable loads type (I) and (II) respectively. This type of load may be called popularly as the dump load. It should be designed as minimum as possible or may be completely avoided in min-grid.

This concept has already been used for smoothing operation of stand-alone hydropower plants without automatic discharge control mechanisms in many developing countries. It may either be an air heater or water heater consuming primarily the active power and hence puts fewer burdens to the power generating units. In another term it is also known as dump load.

Additional, Modified and System's load: The sum of all deferrable loads type (I) and (II) and primary load type (II) forms the additional load to the system. These additional loads together with the primary load type (I) form the modified load. The system's load is the sum of the modified load and the power loss in the system.

6.2 Power and Energy Balance Module

According to the law of energy conservation, the system's power generation must be in balance with the system's power consumption. If $P_{P,i}$ is the capacity of an i^{th}-generating unit and $P_{C,j}$ is the power demand by an j^{th} load, then the power balance for a power system having several power generating and consuming units may be expressed mathematically as,

$$\sum_{j=1}^{m} P_{C\,j} = \sum_{i=1}^{n} P_{P,i} - \sum P_{C,SL} \qquad (6.1)$$

Where,

$\sum_{j=1}^{m} P_{C,j}$	System's load demand	$[kW]$
$\sum_{i=1}^{n} P_{P,i}$	System's power generation	$[kW]$
$\sum P_{C,SL}$	System's power loss	$[kW]$
m	Number of connected loads	$[-]$
n	Number of power generators	$[-]$

Similarly, the total energy balance may be written as:

$$\sum_{j=1}^{m} W_{C\,j} = \sum_{i=1}^{n} W_{Pi} - \sum W_{C,SL} \qquad (6.2)$$

Where,

$\sum_{j=1}^{m} W_{C,j}$	Total energy demand by m loads	[kWh]
$\sum_{i=1}^{n} W_{P,i}$	Total energy generation by n generators	[kWh]
$\sum W_{C,SL}$	Total energy loss in the system	[kWh]

Hence, the present power system comprises the following primary and secondary power generating units:

$$\sum_{i=1}^{n} P_{P,i} = P_{PG} + P_{SG} + P_{AG} \tag{6.3}$$

Where,

P_{PG}	Power supplied by the primary power generators	[kW]
P_{SG}	Power from secondary power generators (e.g., a battery bank)	[kW]
P_{AG}	Power from auxiliary generator (e.g. diesel or gas-fired generators)	[kW]

Similarly, the present power system comprises the following primary and deferrable loads:

$$\sum_{j=1}^{m} P_{C,j} = \underbrace{P_{C,PL(I)} + \underbrace{P_{C,PL(II)} + P_{C,DL(I)} + P_{C,DL(II)}}_{\text{Additional load } (P_{C,AL})}}_{\text{Modified load } (P_{C,ML})} + \underbrace{P_{C,DL(III)}}_{\text{Optional load}} \tag{6.4}$$

Where,

$P_{C,PL(I)}$	Consumer's load (Primary load type I)	[kW]
$P_{C,PL(II)}$	Load due to battery charging (Primary load type II)	[kW]
$P_{C,DL(I)}$	Load due to deferrable load type (I), (e.g. battery charging)	[kW]
$P_{C,DL(II)}$	Load due to deferrable load type (II) (e.g. water pump etc.)	[kW]
$P_{C,DL(III)}$	Load due to dumping excess power (e.g. water or air heaters)	[kW]

And, the system loss may be written as:

$$\sum P_{C,SL} = P_{C,GL} + P_{C,BL} + P_{C,IL} \tag{6.5}$$

Where,

$P_{C,GL}$	Grid loss	[kW]
$P_{C,BL}$	Load due to battery efficiency	[kW]
$P_{C,IL}$	Load due to inverters and other balance of system equipment	[kW]

The power balance equation 6.1 takes the form:

$$\begin{aligned} P_{C,PL(I)} + P_{C,PL(II)} + P_{C,DL(I)} + P_{C,DL(II)} + P_{C,DL(III)} &= P_{PG} + P_{SG} + P_{AG} \\ &\quad - P_{C,GL} - P_{C,BL} - P_{C,IL} \end{aligned} \tag{6.6}$$

Finally, the system's energy balance equation 6.2 for the present power system may be written as:

$$\begin{aligned} W_{C,PL(I)} + W_{C,PL(II)} + W_{C,DL(I)} + W_{C,DL(II)} + W_{C,DL(III)} &= W_{PG} + W_{SG} + W_{AG} \\ &\quad - W_{C,GL} - W_{C,BL} - W_{C,IL} \end{aligned} \tag{6.7}$$

6.3 Power and Energy Balance Algorithm

As discussed in Chapter 2 there is a need for the rational utilization of indigenous resources. Therefore, the development of a computer-supported tool for the parallel assessment of these resources is highly desired. The power and energy balance algorithm is one step forward to fulfil this need. This algorithm is basically designed for the parallel iteration process required for the simulation and optimisation of several components of a power system in each designed time-step. The flow diagram of the developed algorithm is shown in Figure 6.3. This diagram should be consulted parallel with the block-diagram depicted in Figure 2.1, which represents the general form of the present flow diagram.

The Initial System Configuration (ISC) should start (refer Figure 2.1 in Chapter 2) after putting all the necessary information that is collectively called here as the Data Structure (DS). The ISC includes the selection of appropriate power system's components (power generators and load types) manually by selecting '1' for inclusion and '0' for exclusion from the drop-down menu designed in the System Configuration Module (refer section 5.3.2). The simulated values (i.e., the power and energy) from each primary power generating modules, shortly depicted as Hydro, Wind and Solar respectively for hydropower, wind and photovoltaic plants modules are summed up as P_{PG} in the Power and Energy Balance Module. Similarly, all the simulated values (i.e., mainly the power and energy) of each primary load type (I) are also summed up simultaneously as $P_{C,\ PL(I)}$ (see Figure 6.3).

In Figure 6.3 only the flow chart for the power balance is given assuming the importance of the momentary capacity balance of a decentralized power system rather than energy. Therefore, the explanation of this chart is merely based on the power balance.

When charging batteries get charged beyond their full charge, they get destroyed. Hence, all acceptable battery-charging systems switch off the charging current when the required voltage (as function of temperature) is reached. Thus battery charging is an evident use of surplus power, but cannot be regarded as an all time available dump load.

In the power and energy balance module, these values are evaluated against three initial pre-conditions without considering the system losses at first iteration.

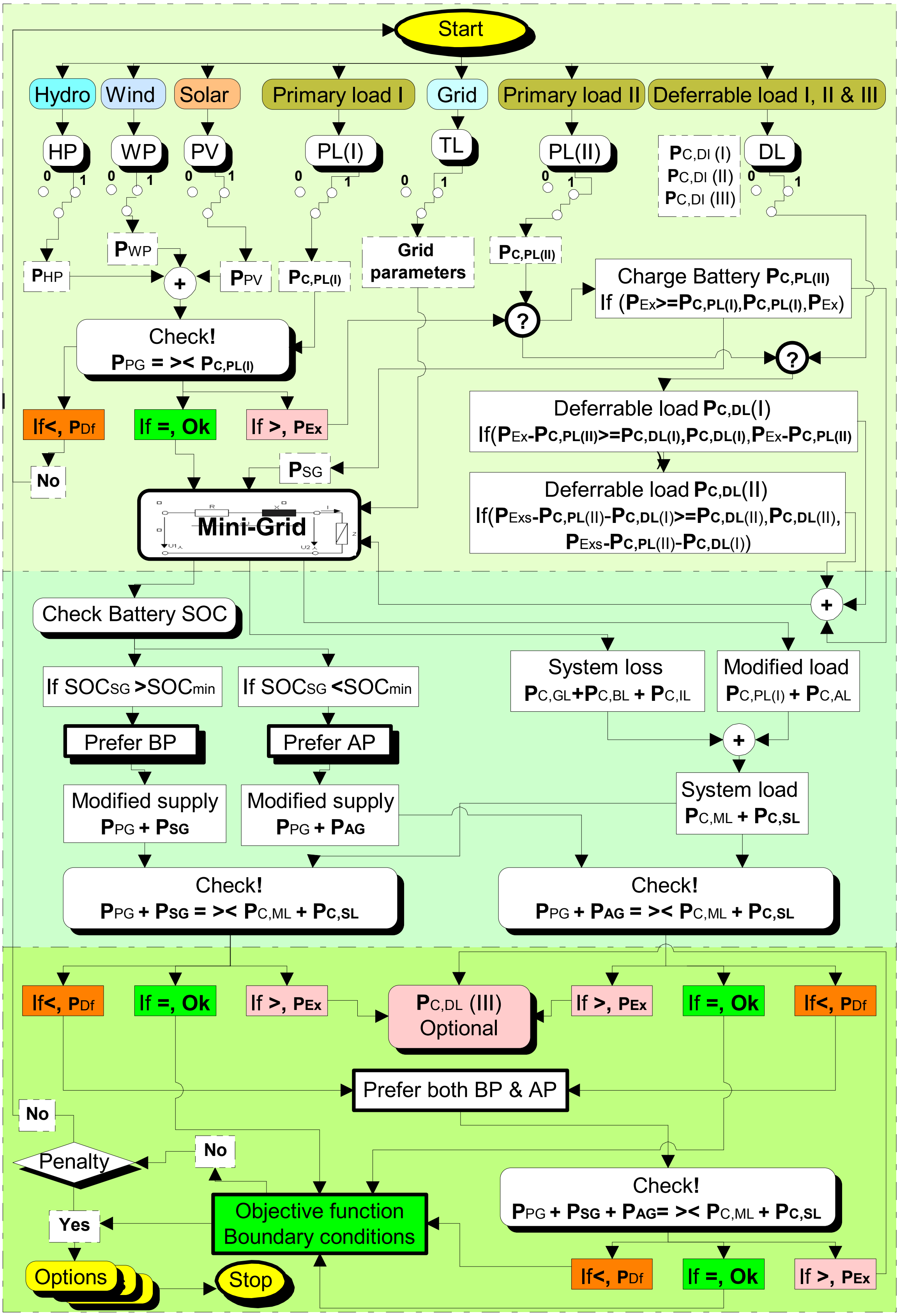


Figure 6.3: Flow diagram for power and energy balance algorithm

The algorithm compares the excess power (P_{Ex}) against the primary load type (II) as pre-conditions during the iteration. This iteration process is explained briefly in Table 6.1.

Table 6.1: Preconditions for the evaluation and command for iteration procedure

<table>
<tr><th>Case</th><th>Precondition</th><th>Evaluation</th><th colspan="3">Command</th></tr>
<tr><td>(a)</td><td>If $P_{PG} = P_{C,PL(I)}$</td><td>ok</td><td colspan="3">Go to Mini-grid Module as primary load</td></tr>
<tr><td rowspan="4">(b)</td><td rowspan="4">If $P_{PG} > P_{C,PL(I)}$</td><td rowspan="4">Excess power (P_{Ex})</td><td rowspan="4">Compare with primary load type (II)</td><td>Sub-preconditions</td><td>Command</td></tr>
<tr><td>(1) If $P_{Ex} \geq P_{C,PL(II)}$</td><td>• Charge battery with $P_{C,PL(II)}$
• Go to Mini-grid as added load</td></tr>
<tr><td>(2) If $P_{Ex} - P_{C,PL(II)} > P_{C,PL(II)}$</td><td>• Dump it using Deferrable load type (III), or
• Opt for using deferrable load type (I)</td></tr>
<tr><td>(3) If $P_{Ex} < P_{C,PL(II)}$</td><td>• Charge battery with P_{Ex}
• Go to Mini-grid as added load</td></tr>
<tr><td>(c)</td><td>If $P_{PG} < P_{C,PL(I)}$</td><td>Deficit power (P_{Df})</td><td colspan="3">• Go back to initial configuration
• Either increase power generation capacity, or
• Decrease the primary load type (I)</td></tr>
</table>

As seen from Table 6.1, there are three cases for preconditions. Let's discuss this algorithm starting from the case (c):

For the case (c), the power balance condition is violated. The algorithm commands to change the initial configuration either by increasing the capacity of power plants or by decreasing the primary load (I). At present only the change in power plant capacity has been envisaged due the reason that the capacity of mini-grid in isolated operation is optimised merely based on the load characteristics.

For the case (b), the algorithm compares the excess power (P_{Ex}) against the primary load type (II). The primary load type (II) in this case is the Battery Bank's (BB) simulated charging load ($P_{C,PL(II)}$), which is given as decision variable. The excess power (P_{Ex}) is the difference between the total power supply (P_{PG}) and the total primary load ($P_{C,PL(I)}$). The case (b) has three sub-preconditions (refer Table 6.2):

1. If the excess power were greater or equal to the primary load type II then the battery will be charged at the rate of its own simulated charging load;
2. The difference ($P_{Ex} - P_{C,PL(II)}$) then must be dumped using deferrable load type (III); and
3. If the excess power were less than the battery's simulated charging load then the battery will be charged at the rate of available excess power.

The battery bank (BB) is used here as secondary power generator (P_{SG}) and should be available to supply the power during deficit. The algorithm directs the value of P_{SG} to mini-grid module for performing its simulation (refer section 5.3.7).

Table 6.2: Preconditions for the use of excess secondary energy in case (b) of Table 6.1

Case	Pre-condition	Evaluation	Command
(1)	If $(P_{Ex} - P_{C,PL(II)}) \geq P_{C,DL(I)}$	ok	• Use the simulated capacity of deferrable load type (I) $P_{C,DL(I)}$ • Go to Mini-Grid module as added load
(2)	If $(P_{Ex} - P_{C,PL(II)} - P_{C,DL(I)}) > P_{C,DL(I)}$	Excess power $(P_{Ex} - P_{C,PL(II)} - P_{C,DL(I)})$	• Dump it using Deferrable load type III, or • Opt for deferrable load type (II)
(3)	If $(P_{Ex} - P_{C,PL(II)}) < P_{C,DL(I)}$	Deficit power (P_{Df})	• Use $(P_{Ex} - P_{C,PL(II)})$ • Go to Mini-Grid module as added load

Battery Bank (BB) is one of the expensive and sensitive components of a power system. BB's operational life will be too short if its cyclic State-of-Charge (SOC) is not regulated properly. Therefore, the SOC must be regulated using appropriate mechanism. In the real-world practice it is performed using a battery charge controller (or a battery charger). The computer simulation of SOC regulation mechanism may also be performed deploying appropriate algorithm. It is done, at present, by defining maximum charging and discharging energy values (in kWh), above which the charging and discharging procedure must cease automatically.

Several strategies for controlling SOC using batteries storage model specially for Wind/Diesel system has been discussed by Manwell and McGowan (1991). A thorough review of a versatile dispatch scheme for remote hybrid energy system is given by Barley (1994). Due to time constraints the battery storage model has been omitted in this work.

The excess secondary power ($P_{Ex} - P_{C,PL(II)}$), which is being dumped may be utilized fully or partially for increasing the load factor and hence for achieving the increased technical efficiency of a power system. For this the developed algorithm evaluates the deferrable load type (I) first against the excess secondary energy.

Similarly, the algorithm is also designed to utilize the excess secondary power ($P_{Ex} - P_{C,PL(II)} - P_{C,DL(I)}$), which is being dumped for the same purpose. This is shown in Table 6.3.

Table 6.3: Preconditions for the use of excess secondary energy for case (b)

Case	Pre-condition	Evaluation	Command
(1)	If $(P_{Ex} - P_{C,PL(II)} - P_{C,DL(I)}) \geq P_{C,DL(II)}$	Ok	• Use the simulated capacity of deferrable load type (II) $P_{C,DL(II)}$ • Go to Mini-Grid module as added load type
(2)	If $(P_{Ex} - P_{C,PL(II)} - P_{C,DL(I)} - P_{C,DL(II)}) > P_{C,DL(II)}$	Excess power $(P_{Ex} - P_{C,PL(II)} - P_{C,DL(I)} - P_{C,DL(II)})$	• Dump it using Deferrable load type III, or • Opt for deferrable load type (II)
(3)	If $(P_{Ex} - P_{C,PL(II)} - P_{C,DL(I)}) < P_{C,DL(II)}$	Deficit power (P_{Df})	• Use $(P_{Ex} - P_{C,PL(II)} - P_{C,DL(I)})$ • Go to Mini-Grid module as added load

For the case (a), the system is in balance and the algorithm directs both values to mini-grid module for performing its simulation.

Mini-grid module supplies information over the grid losses (P_{GL}) and the modified load (P_{ML}). The power simulation module then determines the system load, which is the sum of the system losses (P_{SL}) and the modified load (P_{ML}). In the next iteration step the algorithm evaluates simultaneously the battery's SOC and the system load against the modified supply. Modified supply is the sum of primary, secondary and auxiliary generating capacities.

If the state-of-charge of the BB is (SOC_{SG}) is greater than the minimum state-of-charge (SOC_{min}), then the algorithm prefers the secondary generator (SG). If SOC_{SG} is less than SOC_{min} then it prefers the auxiliary generator (AG). The decision process follows according to given strategy in Table 6.4.

Table 6.4: Preconditions for the use of secondary and auxiliary power generators

Case	Pre-conditions	Evaluation	Strategy
(1)	If $SOC_{SG} > SOC_{min}$	Battery power is sufficient	• Prefer secondary generator (SG). Power from Battery Bank in this case • Go to Mini-Grid module modified supply
(2)	If $SOC_{SG} < SOC_{min}$	Battery power is not sufficient	• Prefer the auxiliary power supply • Go to Mini-Grid module modified supply

In both cases the algorithm evaluates the modified power supply against the modified load in the power simulation module, as shown in Table 6.5.

Table 6.5: Preconditions for the use of either secondary or auxiliary power generators

Case	Pre-conditions	Evaluation	Strategy
(1)	For $SOC_{SG} > SOC_{min}$ If $P_{PG} + P_{SG} = P_{C,ML} + P_{C,SL}$ For $SOC_{SG} < SOC_{min}$ If $P_{PG} + P_{AG} = P_{C,ML} + P_{C,SL}$	ok	• Go to optimisation model • Check against boundary conditions (refer Figure 2.1) • Check of penalty need • Accept the option or repeat the iteration process once again from the beginning.
(2)	For $SOC_{SG} > SOC_{min}$ If $P_{PG} + P_{SG} > P_{C,ML} + P_{C,SL}$ For $SOC_{SG} < SOC_{min}$ If $P_{PG} + P_{AG} > P_{C,ML} + P_{C,SL}$	Excess power	• Dump the excess power $P_{PG} + P_{SG} - P_{C,ML} - P_{C,SL}$ using deferrable load type III • Perform optimisation process as in case 1
(3)	For $SOC_{SG} > SOC_{min}$ If $P_{PG} + P_{SG} < P_{C,ML} + P_{C,SL}$ For $SOC_{SG} < SOC_{min}$ If $P_{PG} + P_{AG} < P_{C,ML} + P_{C,SL}$	Deficit power	• Prefer both the SG and AG • Check against three pre-preconditions again as described in Table 6.5 • Refer Table 6.6

As seen in Table 6.5 (case 1), the algorithm evaluates that the system is in power balance conditions. Then it checks the objective function against the boundary conditions. If the objective function is found acceptable then the project option is accepted and the iteration process ceases. If the objective function is not acceptable then a penalty (refer section 3.2, pp. 28-29) is placed upon to make a project option acceptable. In case of highly reliable power systems the penalty policy is not desired. Then the algorithm repeats the whole iteration process once again (refer Figure 2.1). This process continues till the decision variables in the search space have been evaluated with satisfaction.

In case 2 (see Table 6.5), the algorithm determines the excess power and energy and dumps them using deferrable load type (III). With remaining balanced power, the algorithm repeats the same process as described in foregoing paragraph (case 1).

For case 3 (see Table 6.5), the algorithm determines the deficit of power and energy that must be fulfilled by preferring both the secondary generator (Battery bank in this case) and the auxiliary generator (diesel or gas-fired). In this way the algorithm performs the same steps as depicted in Table 6.5, which is shown in Table 6.6.

Table 6.6: Preconditions for the use of both secondary and auxiliary power generators

Case	Pre-conditions	Evaluation	Strategy
(1)	If $P_{PG} + P_{SG} + P_{AG} = P_{C,ML} + P_{C,SL}$	ok	• Go to optimisation model • Check against boundary conditions (refer Figure 2.1) • Check of penalty need • Accept the option or repeat the iteration process once again from the beginning.
(2)	If $P_{PG} + P_{SG} + P_{AG} > P_{C,ML} + P_{C,SL}$	Excess power	• Dump the excess power $P_{PG} + P_{SG} + P_{AG} - P_{C,ML} - P_{C,SL}$ using deferrable load type III • Perform optimisation process as in case 1
(3)	If $P_{PG} + P_{SG} + P_{AG} < P_{C,ML} + P_{C,SL}$	Deficit power	• Go to optimisation model • Check against boundary conditions (refer Figure 2.1) • Check of penalty need • Accept the option or repeat the iteration process once again from the beginning.

As may be noticed in Table 6.6 the algorithm finally continues its iteration process by simulating the appropriate decision variables till the objective function is satisfied against the boundary conditions.

6.4 Power System Optimisation Module

6.4.1 Objective Function

It includes mainly the economic and technical performance indices that may provide useful information to decision makers. Depending upon the nature of the project and the need of information for decision-makers, the objective function may be to select only one or all of the following objectives:

- Minimize the life-cycle cost,
- Minimize the cost of energy,
- Maximize the system efficiency,
- Maximize the net present value

The present model allows users to select an appropriate objective function as demanded by the decision-makers. However, in the present work it is possible to optimise only one object function at a time. The other information mentioned above is also relevant to the chosen objective function and therefore will also be determined simultaneously (see Chapter 3).

Since the cost-of-energy (COE) in ¢/kWh contains the economic and technical characteristics required to determine the lowest possible size of a power system, it has been selected as the objective function in this work. To a private power producer the minimum value of COE serves as a threshold for the power purchase agreement (PPA). It is assumed here, that if the energy is sold at this cost, then the project will be in break-even after which it will be profitable to the power producer. Therefore, the objective function is to minimize the COE, which is defined as the ratio of total annual cost to total annual energy production. Mathematically it is written as:

$$COE = \frac{\dfrac{r^*(1+r^*)^t}{(1+r^*)^t - 1} \cdot \left[\sum_{K=1}^{n} \left(\sum_{i=1}^{j} I_i \right)_K \cdot (1+r^*)^K + \dfrac{1}{(1+r^*)^t} \cdot I_{rein,i} \right] + \sum_{i=1}^{j} I_{O\&M,i}}{P_{inst} \cdot m_{P,sys} \cdot \eta_{sys} \cdot 8760} \tag{6.5}$$

Where,

$\left(\sum_{i=1}^{j} I_i\right)_K$	Total initial investment on i[th]-system's components (i = 1,2,3,…,j) in year K	[$]
$\sum_{i=1}^{j} I_{O\&M,i}$	Total annual operation and maintenance cost of i[th]-system's components (i = 1,2,3,…,j)	[$]
$I_{rein,i}$	Reinvestment on i[th] system's component (i = 1,2,3,…,j)	[$]
K	Construction phase	[a]
n	Number of construction phase	[–]
P_{inst}	Installed capacity of power system	[kW]
$m_{P,sys}$	System load factor	[–]
η_{sys}	System efficiency components	[–]
t	Time variable in an economic life (t = 1,2,3,…T)	[a]

The total investment cost is determined as the sum of individual components of the power system.

$$\sum_{ii=1}^{j} I_i = I_{HP} + I_{WP} + I_{PV} + I_{BB} + I_{MG} + I_{DL(I)} + I_{DL(II)} + I_{DL(III)} \quad (6.6)$$

Where,

I_{HP}	Initial investment on hydropower facilities	[$]
I_{WP}	Initial investment on wind power facilities	[$]
I_{PV}	Initial investment on photovoltaic facilities	[$]
I_{BB}	Initial investment on battery bank facilities	[$]
I_{MG}	Initial investment on mini-grid facilities	[$]
$I_{DL(I)}$	Initial investment on deferrable load type (I) unit	[$]
$I_{DL(II)}$	Initial investment on deferrable load type (II) unit	[$]
$I_{DL(III)}$	Initial investment on deferrable load type (III) unit	[$]

6.4.2 Decision Variables

Decision variables are the system sizes that must be selected in combination of others within the boundary conditions. Table 6.7 depicts the decision variables that can be simulated and optimised using DEPSO at present.

Table 6.7: Decision variables for optimisation

No.	Power system component	Decision variables	Dimension
1	Hydropower	• Percent of time rated flow equalled or exceeded • Penstock diameter • Penstock thickness • Canal freeboard safety factor • Flow control through turbine	[%] [m] [mm] [-] [%]
2	Photovoltaic plant	• PV array size • Collector slope angle • Surface azimuth angle	[m²] [deg] [deg]
3	Wind power plant	• Wind rotor diameter • Turbine hub height	[m] [m]
4	Energy storage	• Size of battery bank (Primary load II)	[kWh]
5	Deferrable loads	• Size of deferrable load type I, Battery • Size of deferrable load type II Water pump • Size of deferrable load type III Water heater	[kW] [kW] [kW]
6	Mini-grid	• Transmission voltage • Conductor size	[kV] [mm²]

These variables are arranged in matrix form in such a way to ease the implementation of available commercial optimisation software (e.g., Evolver, Palisade, 2004).

6.4.3 Boundary Conditions

They consist of the constraints imposed upon to participating system components. In fact they are imposed in order to confine the search space for optimum configuration of the components. Boundary conditions are broadly classified as hard conditions and soft conditions. Hard boundary conditions are those, which must be fulfilled during the process of optimisation. They are both necessary and important constraints. In fact hard boundary conditions have been used to develop the power and energy balance algorithm. Table 6.8 depicts hard boundary conditions to check the optimum configuration of the system as a whole.

Table 6.8: Hard boundary conditions for optimisation

No.	Boundary conditions		Formula	Symbol	Predefined
1	Storage balance	Minimum battery state of charge	SOC_{min}	≥	Actual from battery type
		Maximum battery state of charge	SOC_{max}	≥	Actual from battery type
2	Capacity and energy balance	Capacity balance	$\sum_{i=1}^{n} P_{P,i} - \sum_{j=1}^{m} P_{Cj} - \sum P_{C,SL}$	≅	0
		Energy balance	$\sum_{i=1}^{n} W_{Pi} - \sum_{j=1}^{m} W_{Cj} - \sum W_{C,SL}$	≅	0
3	Excess power and energy	Excess power	P_{Ex}	≅	0
		Excess energy	W_{Ex}	≅	0
4	Installed capacity	Max. system power supply	$\sum_{i=1}^{n} P_{P,i}$	≤	Installed capacity
		Max. system load	$\sum_{j=1}^{m} P_{Cj}$	≤	Installed capacity
5	Mini-grid	Max. voltage drop	ΔU_{max}	≤	5%
		Max. grid power loss	$P_{C,GL}$	≤	5%
		Max. grid energy loss	$W_{C,GL}$	≤	5%
		Current carrying capacity	I_{max}	≤	Actual for conductor materials

Soft boundary conditions, on the other hand, are required to check the simulated size of individual components. These are the additional conditions imposed to the system. They are important but not necessary conditions for the system's optimality. Their use increases the search space.

Therefore, it is allowed that some of these conditions may be left without consideration in order to shorten the search process. The soft boundary conditions presented in Table 6.9 are modelled at present only for hydropower components.

Table 6.9: Soft boundary conditions for optimisation of hydropower components

Boundary conditions	**Formula**	**Symbol**	**Predefined**
Check for canal free board	$H(F-1)$	$\geq$	User's defined
Check for minimum head loss in conduit in %	h_l	$\leq$	User's defined
Minimum penstock thickness	t_{min}	$\geq$	$t_{min,per} = 10 \cdot \frac{(D_P + 50)}{400}$
Check for Hoop stress (penstock structural safety)	S	<	Half of yield stress
Check for jet ratio (Pelton turbine)	$\frac{D_P}{d_J}$	$\geq$	9 [Giesecke und Mosonyi, 2003]
Check for specific speed for (Pelton turbine)	$n_{q,D}$	$\leq$	Allowable $n_{q,D}$
Check for permissible static draft head	h_s	$\leq$	$h_{s,crit}$

H	Water depth in canal		$[m]$
F	Safety factor against overtopping due to water surge in canal		$[-]$
$t_{min,per}$	Permissible minimum thickness of pipe against corrosion		$[mm]$
d_J	Jet diameter (only for Pelton turbine)		$[m]$
Allowable $n_{q,D}$	$17.53 \cdot \sqrt{\mu_P} \cdot (0.5445 - 0.0116 \cdot n_{q,D})$	μ_P Jet flow coefficient. [Giesecke und Mosonyi, 2003]	$[min^{-1}]$
S	$\frac{\rho \cdot g \cdot H_{max} \cdot D_P}{2t_e}$	ρ Density of water g acceleration due to gravity	$[N \cdot m^{-2}]$
H_{max}	$H_{gros} + H_{Surge}$.	H_{gros} Gross head H_{Surge} Surge head	$[min^{-1}]$
D_P	Penstock diameter.		$[m]$

The results of the optimisation process are acceptable only if all of the hard and soft boundary conditions are fulfilled.

6.4.5 Presentation of Results

It consists of two parts:

Analytical result: It contains all necessary information on optimised technical and economic parameters and indicators required by decision makers. The following information on system characteristics is included as results of simulation and optimisation process:

Table 6.10: Technical and economic parameters required for decision making

Analytical result	Parameters	Dimension
Technical parameters include:	1. Daily maximum load and power	$[\mathrm{kW}]$
	2. Daily minimum load and power	$[\mathrm{kW}]$
	3. Daily average load or power	$[\mathrm{kW}]$
	4. Daily energy demanded and supplied	$[\mathrm{kWh}]$
	5. System load ratio	$[-]$
	6. System load factor	$[-]$
	7. System utilization factor	$[-]$
	8. System performance index	$[-]$
	9. System improvement ratio	$[-]$
	10. Energy index of reliability	$[-]$
	11. Mini-grid efficiency	$[\%]$
	12. Annual Energy production	$[\mathrm{kWh}]$
Economic parameters include:	**Project Cost**	
	1. Initial investment	$[\$]$
	2. First year distribution	$[\$]$
	3. Second year distribution	$[\$]$
	Economic Indicators	
	4. Present value of cost	$[\$]$
	5. Present value of benefit	$[\$]$
	6. Net present value	$[\$]$
	7. Cumulative net cash flow	$[\$]$
	8. Year to positive cash flow	$[\mathrm{Year}]$
	9. Simple payback period	$[\mathrm{Year}]$
	10. Benefit-cost ratio	$[-]$
	11. Break-even energy value	$[\$ \cdot \mathrm{kWh}^{-1}]$
	12. Profitability index	$[-]$

Graphical result: To support the visualization of the generated results the following graphs have been included:

- DPS grid showing all power supply and consumption nodes
- Power demand and coverage curves
- Load and power flow duration curves
- Battery state-of-charge curve

- Cash flow curve

6.4.6 Sensitivity Analysis

The present model also allows performing sensitivity analysis of the optimised project parameters according to various scenarios against the base case. Table 6.11 presents two scenarios for sensitivity analysis that have been modelled at present. These are demand and supply scenarios.

Table 6.11: Scenarios for sensitivity analysis

	Scenario		**Sensitivity Analysis**	Pessimistic	Optimistic	IRR
1	**Demand**	Consumer demand	Investment increase	10 %		8 %
			Investment decrease		10 %	10 %
			Benefit increase		10 %	12 %
		Potentially saleable demand	Benefit decrease	10 %		14 %
			O & M increase	10 %		16 %
			O & M decrease		10 %	18 %
		Potentially saleable demand plus penalty	Interest increase	10 %		20 %
			Interest decrease		10 %	22 %
			Economic life increase		10 %	24 %
2	**Supply**	Hydropower	Economic life decrease	10 %		26 %
		Wind power	Replacement cost increase	10 %		28 %
		Photovoltaic	Replacement cost decrease		10 %	

Demand scenarios include checking system's performance at various demand categories, namely: consumer demand (Primary load type I); potentially saleable demand (Primary load type I and deferrable load type I & II) and a penalty is added to see whether the system perfumes economically acceptable manner even if the demand is not fully satisfied (as discussed elsewhere in section 3.2 and 6.1.2)

For each scenario, the sensitivity analysis is performed under three categories: namely pessimistic considering all cost increased by 10 % and benefit decreased by 10 %; Optimistic considers that all costs are decreased by 10 % whereas benefit increased by 10 % and finally the model iterates the scenario for different discount rate in order to determine the internal rate of return (IRR).

7 APPLICATION

7.1 General

With the motivation to study small-hydro-based renewable power system for rural electrification, the author selected two remote regions of Nepal for the case studies. One site lies in Mustang district and another one lies in Solukhumbu district in the north-western and north-eastern part of Nepal respectively. The experience survey conducted by the author was fruitful for getting insights of the energy situation in Nepal, in general, and for the site selection for future rural electrification in particular. All visited places were attractive for tourists. These places were selected as priority areas because the demand for electrical energy exists, the consumers have willingness to pay and these areas are causing deforestation.

During field visit, the author conducted an experience survey of key informants on the present use of energy sources. Because of the lack of proper instrumentation, it was not possible to measure on-site hydro-meteorological data. The present data are basically collected from secondary sources [refer Appendix II]. One of the encouraging aspects of these two sites is the load centre. Since these sites are located in very busy tourist route (areas) one can easily assume the viability of such project. The author hopes that once the reliable energy technology is available for people, it may boost employment and other peripheral development activities. Consequently, the deforestation will be stopped and the rural population will be equally benefited. The prospect of disseminating decentralized power system in Nepal is discussed in Chapter 8 as epilogue of the present work.

7.2 Junbesi Rural Electrification (JURE): A Case Study

7.2.1 Site Description

The Beni village development committee is located in the Junbesi valley at an altitude ranging from 2500 m to 3400 m. This valley has been important for both locals and tourists because of two Monasteries, Thupten Choling and Phunmoche. It is also the gateway to Mt. Everest. The Junbesi valley is situated 20 km north at walking distance from the nearest airport and the market centre at Phaplu in Solukhumbu district. Most earnings of the inhabitants in this VDC come from subsistence farming and forestry. Tourism is the main source for cash income.

The growing population and the tourists' visits in this regions demand a huge amount of energy supply. Firewood is the main source of heating and cooking, whereas candles and kerosene are primarily used for lighting. Only few villages viz., Najing, Junbesi, Mopun and Thupten Cholin have access to electricity from four stand-alone hydropower plants. The existing power demand and supply data of this site (see Table 7.1) are based on E&Co (2000) and supplemented appropriately by the author after his field visit in February 2001.

Table 7.1: Data structure from the Junbesi case study area

Location	Electric power demand (kW)	Supply (kW)	Future extension (kW)	Installed capacity (kW)
Junbesi	37	6	-	6
Thupten Choling	30	6	-	6
Mopun	20	20	25	25 + 25
Tractor	9.5	-	-	-
Sulabesi and Najing	8	16	-	16
Thumbuk	6.5	-	-	-
Other Hamlets	5	5	-	-
Total hydro plants (Existing)	**116**	**53**	**25**	**78**
Phunmuche hydro plant (planned)	30	-	30	30
11 kV SCECO grid to JREP	146	~30 peak	1400	400

After a preliminary estimate of Junbesi valley power demand with 300 households indicates that there exists a peak electric power demand of 150 kW at 53 % load factor. This demand has been partially covered by four stand-alone micro-hydropower plants having a total installed capacity of 53 kW. To cover the deficit, two alternatives were proposed and assessed by E&Co. (2000). These were:

a) To increase generation by 80 kW through a new stand-alone hydropower plant from a river near Junbesi village,

b) To extend a 22 km long 11 kV grid (~30 kW at peak) from Salleri-Chialsa Electric Company (SCECO[10]) to this valley and add a 25 kW generator at Mopung hydropower plant under Junbesi Rural Electrification Project (JURE).

The E&Co. has concluded the alternative (b) as the feasible alternative.

This alternative does also have some drawbacks, which have been discussed by [Maskey et al, 2002. Except Mopun plant with 50 kW of capacity, this alternative does not consider the integration of other existing micro-hydropower plants at Najin, Junbesi, and Thupten-Choling with the SCECO grid]. This is because of the unwillingness of SCECO purely due to technical reasons. On the other hand, electricity from SCECO to Junbesi VDC is only for daytime use. Though SCECO plans to extend its installed capacity up to 1400 kW in near future, the present installed capacity is only 400 kW [Personal communication with the managing director of SCECO]. It has already reached a peak of 370 kW.

[10] SCECO (400 kW), a highly successful community-owned power company in Sallery of Solu-Khumbu district, began its production only in 1986 after 26 years of time lag from its first investigation. It was funded and technically supported by Swiss Development Cooperation and is managed and operated by locally trained personnel. It has 20 km long transmission lines with a capacity of 11kV. It serves about 1000 households in those regions and has reached its peak power demand of 370 kW in 2001 [Widmer, and Arter, 1992; SCECO, 2000; E&Co, 2000]. Most of the input data for the case study has been taken from SCECO.

Further, this alternative will have a negative consequence on the REC of the existing power plants in this valley. Since these plants will not be used anymore, the already frustrated REE of existing plants might leave the village forever. The risk of out-migration has been a big problem in this valley[11]. Moreover, E&Co did not consider a planned 30 kW hydro-plants at Phunmoche as a possible alternative for power supply because the electrification from SCECO gird was primarily considered for electrification up to Thupten-Choling Monastery. Phunmoche Monastery lies ~2 km farther from Thupten-Choling.

Based on the data from existing photovoltaic power plants (8 kW) and the recorded wind velocity of 5 m/s at Phaplu airport during the study visit, it may be fairly assumed that there is a good potential for wind and solar energy technologies. Unfortunately, the long-term recorded data on wind velocity and solar radiation was not available at the airport. After an interview with the tower operator, it was revealed that the wind velocity might exceed 30 m/s. The present hypothetical project needs time series wind velocity to verify the applicability of the developed models. Egger et al (2002) generously provided the author a 2–minutes averaged time series of wind and solar data recorded for two winter months at a camp near the Jomsom airport. Considering roughly the topographical and meteorological similarity of Mustang and Junbesi valley, the author assumes that these data may be applicable to this hypothetical project.

Considering the above points, a third alternative using micro-hydropower plants based decentralized power system connecting all existing and planned hydropower plants together with some RETs (e.g., Wind and photovoltaic power plants) has been analysed. Nine options involving different combinations of power plants have been analysed. Among them were a purely hydro option and a hydro-battery storage option. The hypothetical Junbesi Rural Electrification scheme is shown in Figure 7.1.

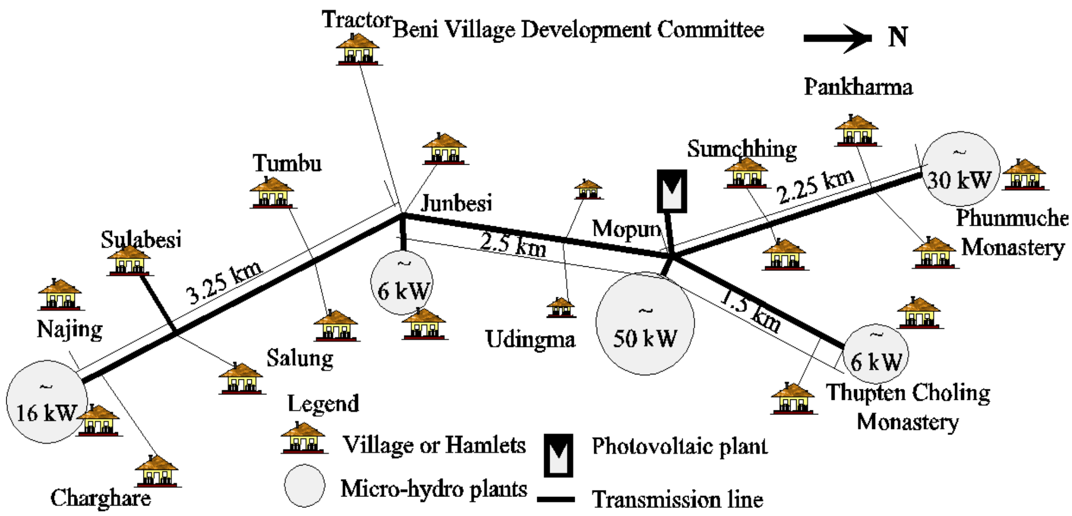


Figure 7.1: A hypothetical micro-hydro based mini-grid system with solar electric plant

[11] Personal communication with key informants was conducted by the author during his field visit in February 2001.

For the present analysis, the author made the following assumptions, the details of which is presented in data input checklist (refer Annex II):

- All existing and planned micro-hydropower plants in Decentralized Power System (DPS) supply power constantly at full capacity.
- DPS includes photovoltaic and wind power plants wherever possible.
- The peak deficit of 42 kW is covered through the stored energy in the battery banks.
- The battery banks are charged during excess energy and discharged during power deficit.
- Any power fluctuation is controlled through deferrable loads and battery supply as discussed in Chapter 6.
- A time-series hourly-averaged solar radiation and wind velocity recorded for Mustang valley is considered.
- The initial investment costs were determined using cost-functions discussed in Chapter 4.
- Allowance is made for operation and maintenance and for upgrading existing plants as percentage of initial investment of respective system's components.
- A 32-year project life with an annual discount rate of 8 % is considered for economic analysis as the base case.
- Sensitivity analysis was also performed considering the parameters described in section 6.1.2.

7.2.2 Application

For the present analysis, an electrical equivalent diagram of the 12 km long transmission line having five nodes for power intake and nine nodes for power off-take has been modelled (see Figure 6.7.4). Figure 7.2 shows an equivalent electrical diagram of the hypothetical mini-grid scheme (refer Figure 7.1).

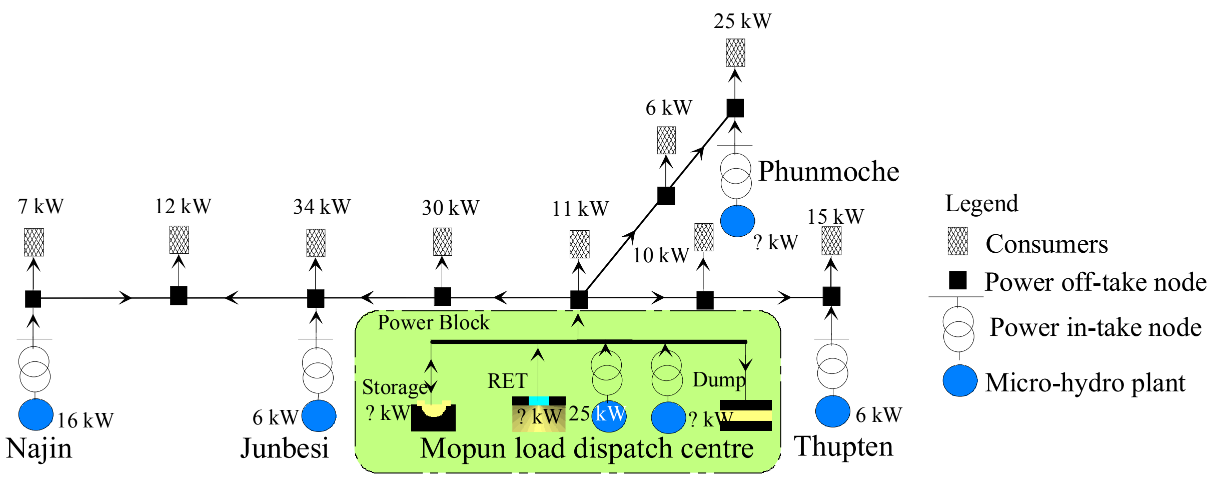


Figure 7.2: A hypothetical micro-hydro based mini-grid system with RET

The present aim is to discuss only one option of a mini-grid with five hydropower generators, one wind, and one photovoltaic power plant with a storage facility to demonstrate the functionality of the proposed model.

Among the power intake nodes, one node is connected to a 'power block' that consists of two micro-hydro plants, one photovoltaic plant, one wind power generator, one battery bank and several deferrable loads. This 'power block' is located at Mopun and considered as the central load dispatcher. The size of this 'power block' and one micro-hydro plant at Phunmoche has been simulated and optimised by keeping the capacities of the other hydro plants at Najin, Junbesi, Thupten and Mopun villages constant for 24 hours. The evaluation is based on the daily technical performance by limiting the voltage drop and the power loss at each node below 5 %. The transmission voltage and the conductor size are fixed at 3 kV and 50 mm² (Cu) respectively and the components' efficiency is also considered.

As load data input, the author considers sufficient to use the system demand pattern similar to SCECO load pattern. It is assumed that, once the electricity is available, the daily load demand pattern of this site would be similar to its neighbouring SCECO daily load pattern. It should be noted here that the present load pattern of SCECO is a gradual growth due to its decades of success operation. Consideration of such a pattern for Junbesi would be very ambitious. Therefore, author's intention is to check the general analytical strength of present model then doing feasibility study of the JURE. Considering the demand of the Phunmoche Monastery and its periphery, the peak demand may reach up to 150 kW. A daily system load curve for a typical winter month, which characterises a daily energy demand of 1956 kWh, is presented in Figure 7.3.

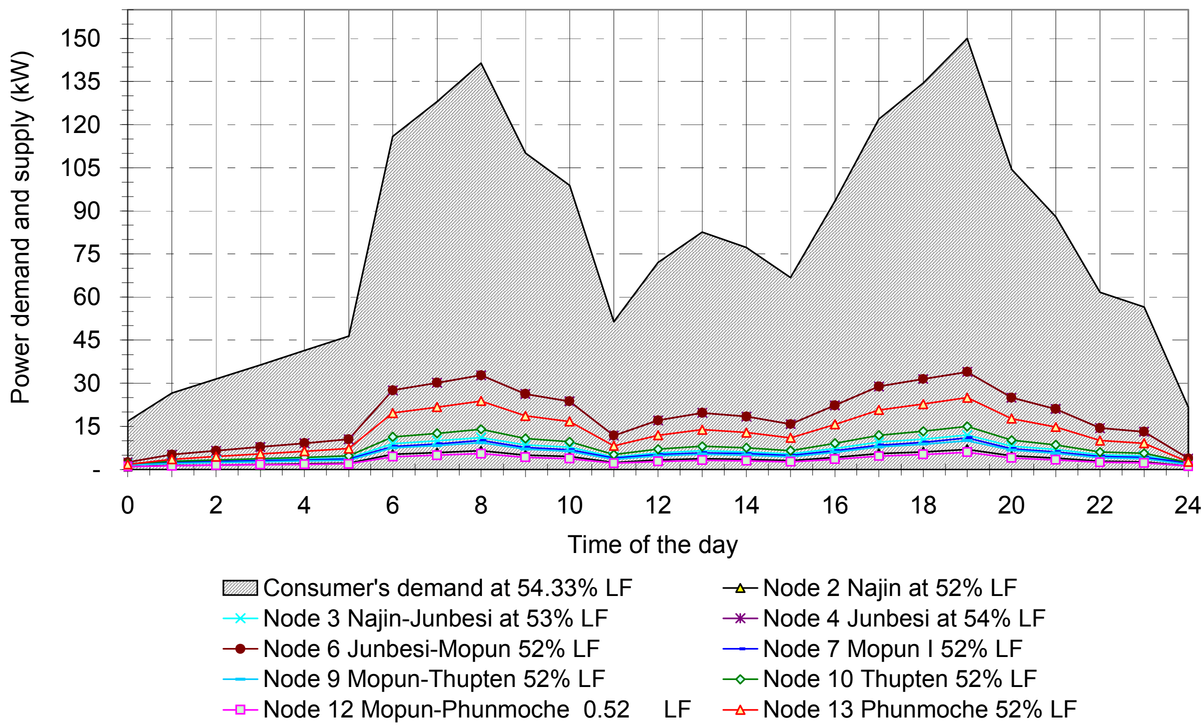


Figure 7.3: Daily consumer's load curves of a hypothetical power system

It has a load factor (LF) of 54 % and a load utilisation period (T_m) of 13 hours. This implies that a single-source plant would have a plant utilization period (T_n) of maximum 54 %. Such a 'double-humped' load pattern is very rare case for rural electrification. However, considering the rapid tourism development along Junbesi valley, the probability is fairly high to develop such a load pattern in Junbesi valley too.

To determine the best system configuration, the first approach was to cover the base load and a part of the middle load by a combination of four possible existing hydro plants near by Mopun and one new plant at Phunmuche. The model algorithm, as mentioned in Chapter 6, was used to check the performance of the whole system using different sizes of solar plants and battery banks. Author did the assessment using Microsoft Excel 2000.

In order to determine the power flow, voltage drop and power losses, a simplified 'Node point-Potential process' as discussed in section 5.3.7.8 was used. The time series power values were calculated using hydropower, photovoltaic and wind power plant modules as discussed in Chapter 5. The annual energy was extrapolated from the daily energy to calculate the break-even average annual specific electricity cost. At this cost of energy the net present value (NPV) of the investment equalled zero. The economic analysis is based on the annuity method using the discount rate of 8 % per annum and the system's life span of 32 years. The annual investment cost of the participating plants and devices is based on the standard construction practice in Nepal.

7.2.3 Results

This system has been simulated and optimised using the developed tool. Since only one option is considered at present, the iteration was performed manually. Figures 7.4, 7.5 and 7.6 represent its results.

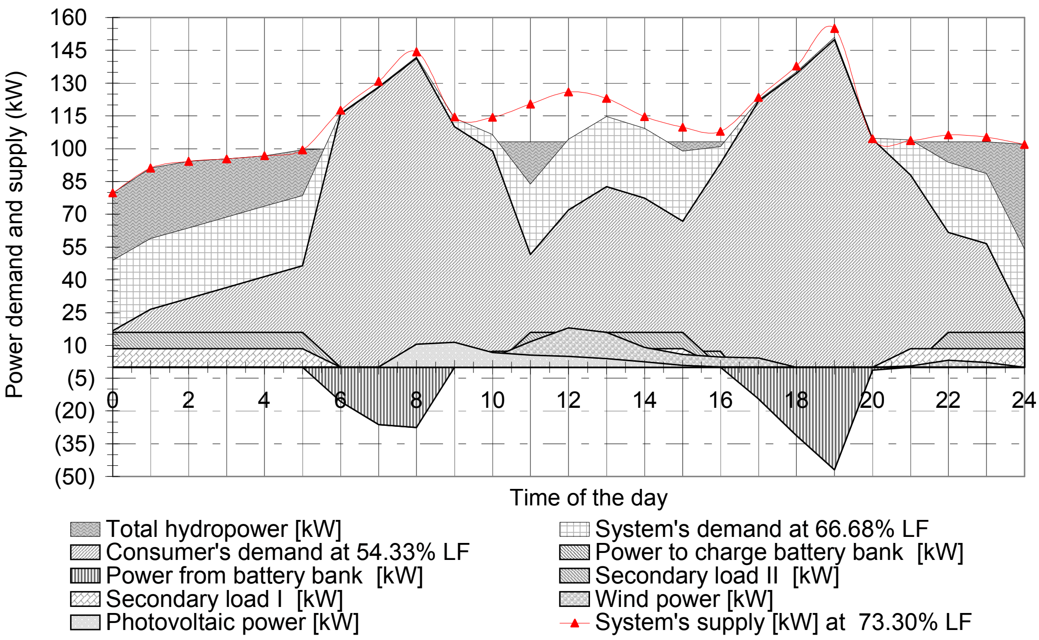


Figure 7.4: Modified demand coverage by option 6 at 73 % load factor

Figure 7.4 shows the time series modified power demand at 73 % load factor completely covered through a combination of hydropower, wind, solar and battery bank (see the top line in Figure 7.4). It also shows the utilization of secondary power and energy using primary load type (II) and deferrable loads type (I) and (II). The system efficiency of this option reached 81 % as compared to its original system efficiency of 54 %.

Figure 7.5 shows the power-scheduling scheme. As can be seen the original consumer's load-duration has nearly 'flatten' due to the use of primary load type (II) and deferrable load types (I) and (II). The excess energy due purely to hydropower plant is stored in the battery for covering the day and the evening peaks. This has increased the system plant utilization factor by 30 %. The modified load factor is raised to 61 %. This naturally implies a better economic utilization of available resources. It should be noted here that the turbine flow is considered 100 %. Detail calculation and other information are presented in Annex II.

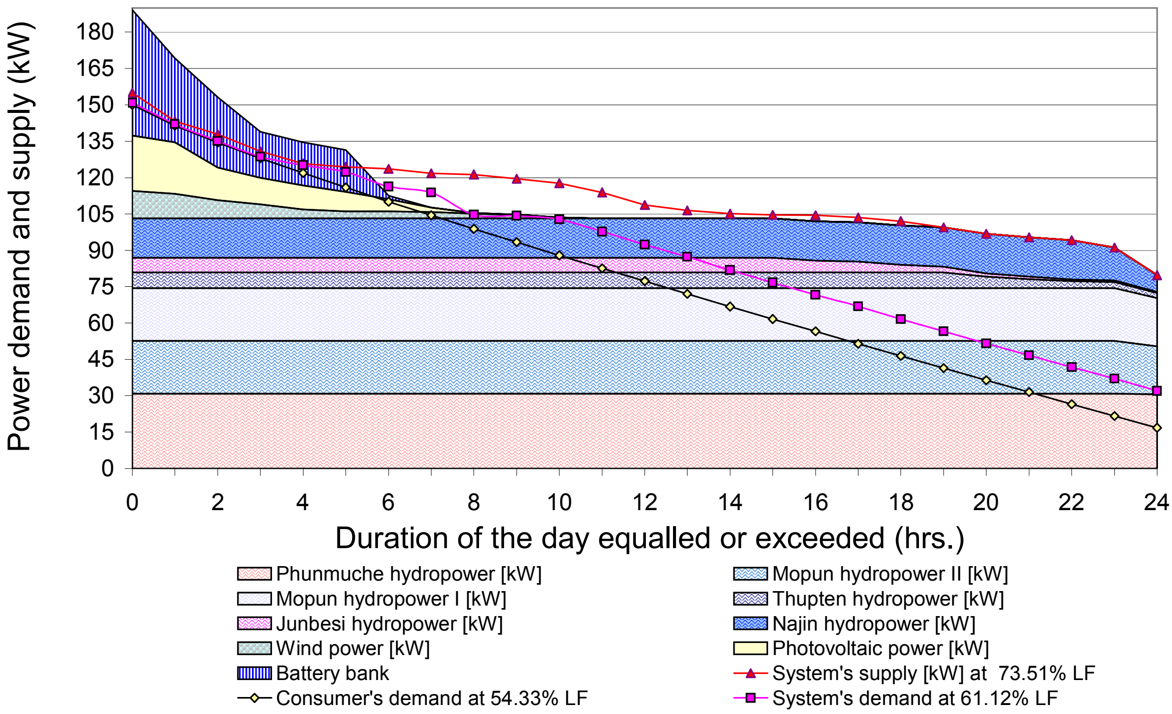


Figure 7.5: Power demand and supply duration curves

Now, let's also discuss the other technical features of the developed model. A series of graphical presentations make the power system's information more visual and explainable. Figure 7.6 depicts two time series curves for charge and discharge patterns of a battery bank and the cumulative energy storage. These curves are useful to monitor the state-of-charge conditions of a battery bank.

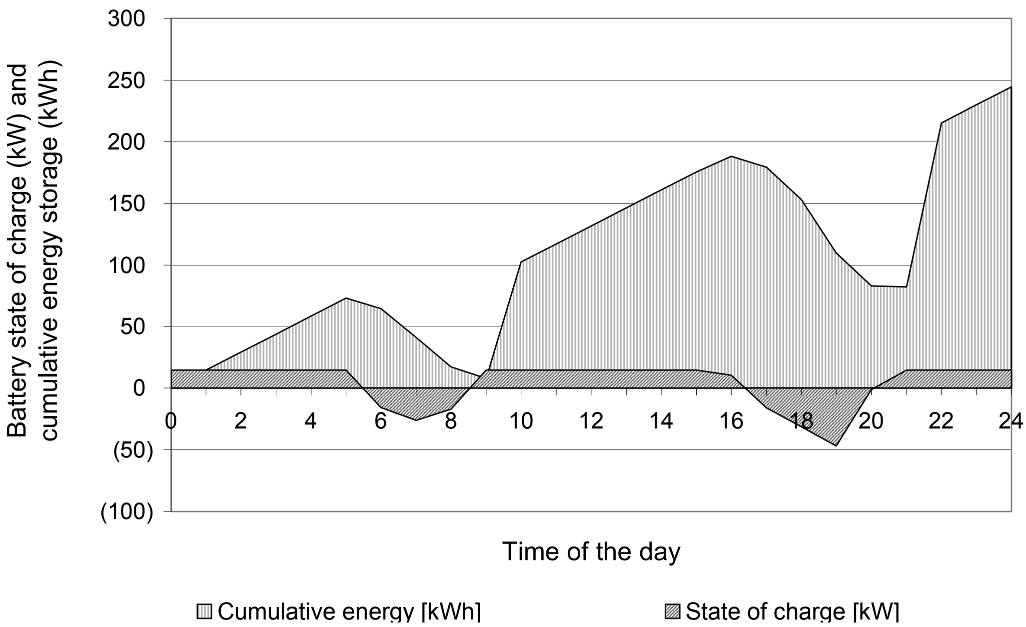


Figure 7.6: State-of-charge conditions of a battery bank

Besides the technical indicators, economic indicators can also be visualised. Figure 7.7 shows the cash flow for cost and benefit stream for which the net present value is zero, benefit-cost ratio unit and the IRR is 8%. The break-even cost of energy is around 0.0146 \$/kWh. This cash flow diagram also shows that the positive cumulative cash flow begins after 11th year of project life.

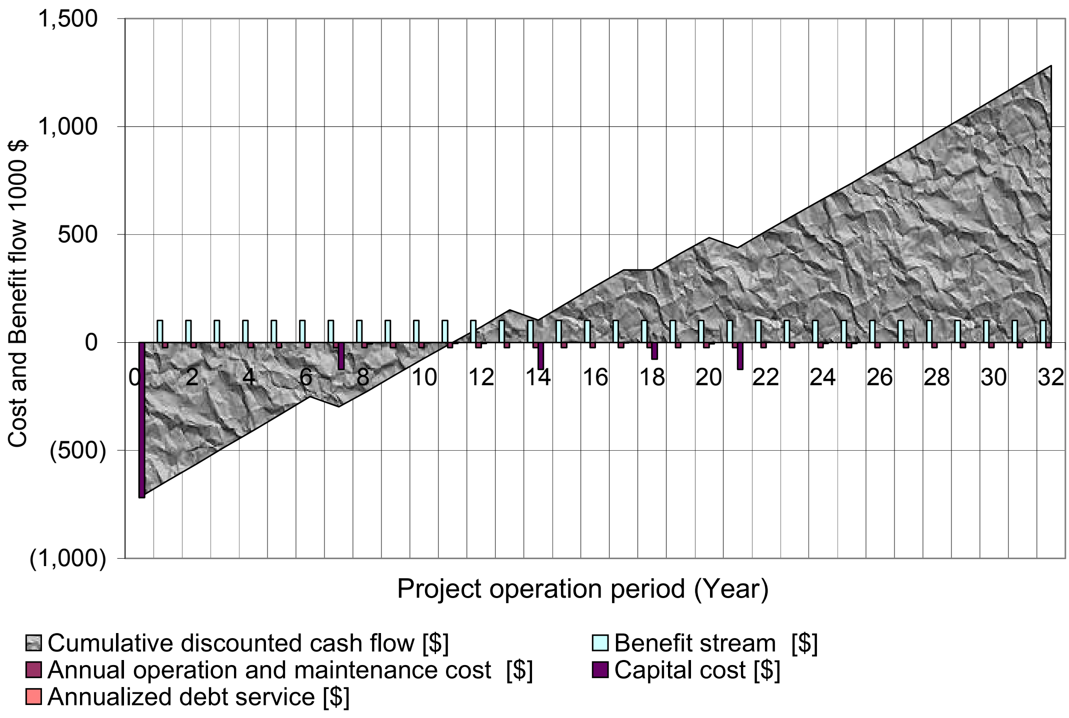


Figure 7.7: Cash flow diagram of capital cost and benefit streams

Figure 7.8 presents three scenarios of sensitivity analysis that also determines the IRR. As can be seen, the project may optimistically earn 13 % return on investment.

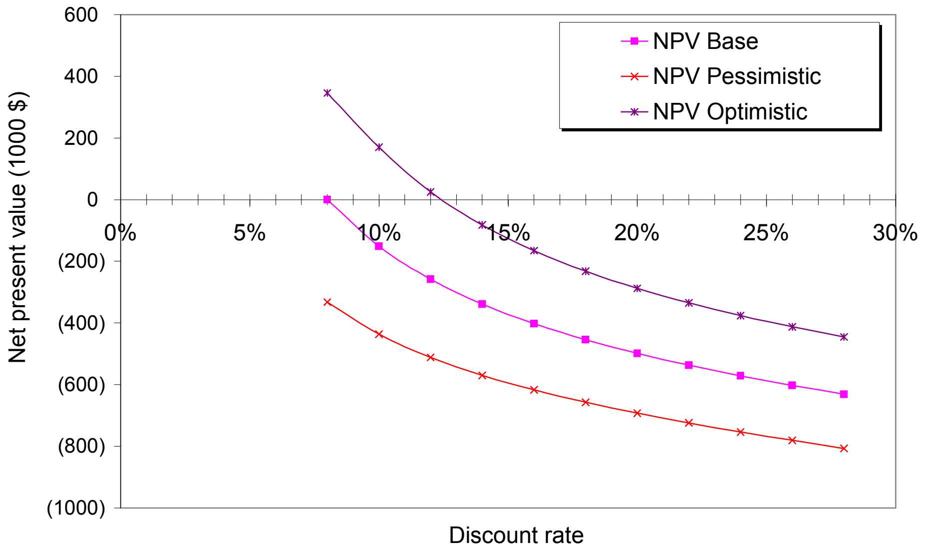
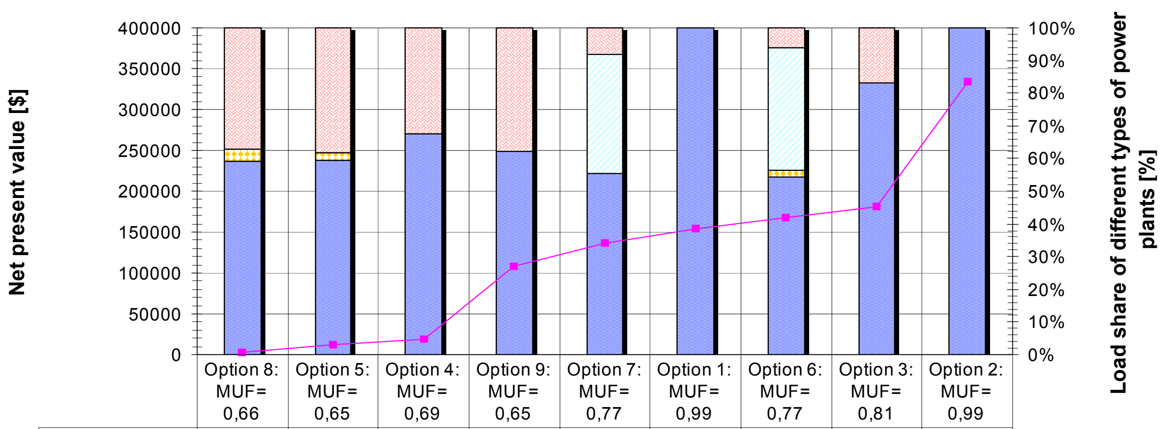


Figure 7.8: Sensitivity analysis and determination of internal rate of return

The present model is also capable of comparing different options based on economic and technical indicators. Using this model Maskey et al (2002) conducted comparison of break-even value (BEV) of electricity for nine options that were obtained according to performance index (PI), and the plant utilization factor (n). Figure 7.9 presents comparison between nine options with positive NPV.



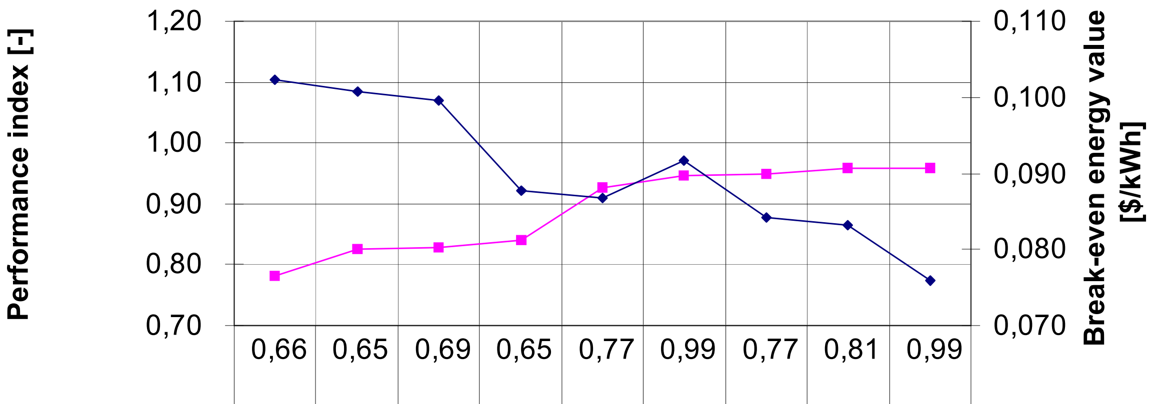
	Option 8: MUF= 0,66	Option 5: MUF= 0,65	Option 4: MUF= 0,69	Option 9: MUF= 0,65	Option 7: MUF= 0,77	Option 1: MUF= 0,99	Option 6: MUF= 0,77	Option 3: MUF= 0,81	Option 2: MUF= 0,99
Storage [kW]	68	69	58	67	16	0	12	31	0
Wind [kW]	0	0	0	0	71	0	75	0	0
Solar [kW]	7	4	0	0	0	0	4	0	0
Hydro [kW]	108	108	120	109	108	216	108	152	202
NPV [$]	2249	12504	18745	107591	136429	153616	167016	181649	334435

Options

Figure 7.9: Comparison between options with net present value

It also shows load shared by different type of power plants.

A comparison between the performance index (PI) and the break-even energy value (BEV) with respect to normalized utilization factor (UF) is shown in Figure 7.10. Figure 7.10 indicates that the best possible options lie within the range of 18-23 UF in hours yielding higher PI and moderately lower average BEV.



	0,66	0,65	0,69	0,65	0,77	0,99	0,77	0,81	0,99
PI [-]	0,78	0,83	0,83	0,84	0,93	0,95	0,95	0,96	0,96
BEV [$/kWh]	0,102	0,101	0,100	0,088	0,087	0,092	0,084	0,083	0,076

Normalized utilization factor [-]

Figure 7.10: Comparison between PI, BEV vs. UF

The multiple hydropower plants with or without storage options (options 2 and 3 in Figure 7.9 and 7.10) are the best among all options yielding highest PI and lowest BEV.

7.2.4 Discussion

Since there are no other additional hydropower potential sites available to satisfy the demand, an integration of existing and planned hydropower plants either with wind and moderately large storage or with wind and photovoltaic energy technologies plus small storage may provide better solutions (Options 6 & 7). It is to be underlined here that the simulated optimum BEV before tax (8.5 cent/kWh) is almost 8 % less than the average retail electricity price before tax (9.2 cents/kWh) from the national grid in Nepal [NEA, 2001]. The average energy value for rural electrification from a stand-alone micro-hydro, at present in Nepal, lies, in order of magnitude, in the range 10 - 15 cents (at Load factor < 40 %).

7.3 Conclusion

With this case study, an example on the application of a hydro-based decentralized renewable power system for rural electrification has been demonstrated. Application of present model answers the three questions raised in Chapter 1 as follows:

Comparing the electricity prices from the national grid and stand-alone hydro plants, the electricity price from small-hydroplants-based DRPS is relatively cheap and affordable. For a complex system like this, the technical and economic indicators play an important role in decision making. As can be seen the developed model is capable of generating necessary information required by the decision makers.

Although it is still in developing stage, its capacity will proved to be valuable for engineers engaged in planning rural electrification. Being modular this tool is highly flexible for further development. The system architecture is however not yet fully developed to make the present tool as user's friendly as possible. However, it can be fairly assumed that the existing technical know-how of developing countries can handle quite well with the operational complexity of such model. Thus, the author concludes that this model in the course of its further development will be helpful for simulating and optimising small-hydro-based renewable power system and for generating necessary information to expedite rural electrification in developing countries.

7.4 Replication of JURE model and future work

The JURE model can be replicated in other remote regions of Nepal. As an example, in the stretch from Kagbeni to Muktinath in Jomsom district, there exist a good potential for the utilization of renewable energy together with several micro hydropower stations. Altogether, 5 stand-alone micro-hydropower plants capacity ranging from 5 kW to 35 kW have been supplying electricity in this region. Although this is a tourist region with high willingness to pay for the electricity, these plants have not been commercially viable. The main reasons are the lack of reliable electricity supply and poor technical backstops. Local people have already started installing solar home system. Kagbeni has a good potentiality for generating wind power at commercial basis. There were two wind generators established some ten years back, but both of them have collapsed since its establishment. This place is being recently connected with a small hydropower station (2 MW) by a 33 kV transmission line grid. These plants can be interconnected with DPS to cover all of the electricity demand of the regions. Many parts of Nepal have such possibilities. These areas must be identified and required action must be carried out in order to rapidly implement the DPS.

8 PROSPECT FOR SMALL-HYDROPLANTS-BASED DRPS IN NEPAL

8.1 General

The preceding chapters dealt with the technical and economic aspects of the developed concept on small-hydro-based decentralized renewable power systems (SHBDRPS) and the applicability of the developed tool for rapid planning of such systems taking a hypothetical case study of Junbesi Rural Electrification Project (JURE). This chapter aims at discussing on the prospect for the development of the SHBDRPS in developing countries using a case study of Nepal's rural electrification policy. Since the motivation to conceptualise the present work was heavily based on data and the working experience in Nepal, this Chapter should also serve as the epilogue of the present work.

8.2 Energy Options for Electrification in Nepal

Nepal is rich in her snow-fed water resources and bio-diversity. The altitude and various climatic conditions force to use diverse sources of energy supply. Within 250 km of cross-section, the difference in relief rises from 70 m to more than 8000 m above mean sea level. Accordingly, the appropriateness of non-traditional energy sources also varies with the altitude (see Figure 8.1).

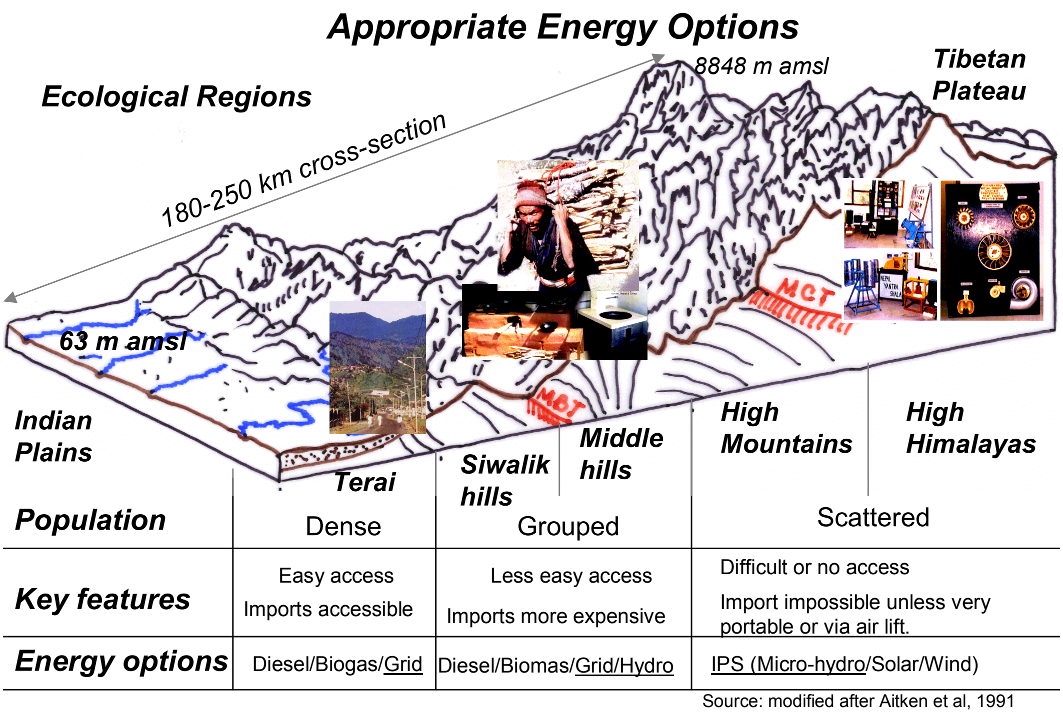


Figure 8.1: Characteristics and energy options in Nepal (source: modified after Aitken et al, 1991)

Tropical Terai plain (see Figure 8.1) has got higher population density, denser forest, fertile agricultural land, good road network and other infrastructures as compared to hilly and mountainous regions. It has been thus appropriate to provide energy from biogas, diesel, and national electric grid system. In the middle hills, where few roads and other infrastructures are available, a diesel-hydro option has been considered suitable. Because of the difficult terrain, the extension of the central grid is not economically and technically feasible in high mountainous regions [Banskota et al, 1990]. Thus, decentralized mini/micro hydropower or other renewable energy technologies (solar, wind, biomass gasifier, etc.) as well as rehabilitation of existing pani-ghatta (watermills) become the most suitable options [Aitken et al, 1991].

Almost 87 % of 24 Million people reside in rural areas of Nepal. Among them, about 60 % of rural population lives in the hilly and mountainous regions. The present energy need in the remote areas of Nepal has been met through traditional firewood, animal dung, and agriculture residue and human or animal power. This traditional way of energy supply has been insufficient and has enormous negative impact on environment, especially near the tourist regions. As the country possesses no significant fossil fuel deposits, the dependence on the imported commercial fuel is placing an increasing demand on foreign exchange. Sufficient energy is desirable to strengthen self-reliance of the rural people and that should be clean to protect their surroundings. In that sense, electrification of remote regions using renewable energy technologies has been sought frequently. Electricity has been popular, especially in the tourist attraction centres, where there exist both: a huge demand for electricity and willingness to pay for it. However, the lack of reliable electricity is hindering the development of rural economy, on one hand, and rapidly destroying almost depleted forest on the other hand.

The rising demand for energy and the stringent criteria to protect environment have prompted the use of renewable sources of energy. Decentralized renewable power systems based on biogas, enhanced biomass, micro-hydro, solar, photovoltaic, etc., provide feasible energy supply options that are clean in terms of greenhouse gas (GHG) emission and also meet the concerns of social justice in rural areas. Socio-economic effects from increased supply of modern energy such as electricity from renewable energy technologies (RETs) are multifaceted. However, low energy density from RETs demands to construct large systems. Consequently, they are expensive for developing countries like Nepal.

8.3 Policy for Rural Electrification in Nepal

Rural electrification is pre-requisite for the poverty alleviation and overall economic development of Nepal [Neupane, 2004]. Nepal’s rural electrification can broadly be classified into NEA’s grid-based rural electrification and isolated rural electrification [CES, 2000]. CES further classified isolated rural electrification into NEA’s isolated electricity generation through small hydropower and private-owned electricity generation facilities like small and micro-hydro and other renewable energy technologies (solar, wind etc.). At present both public and private sectors as well as non-governmental organizations (NGOs) are engaged in rural electrification in Nepal [CES, 2000].

The Directorate of Rural Electrification Program under Small Hydropower Department (SHPD) of Nepal Electricity Authority (NEA) is responsible for planning, generation, transmission and distribution of public grid-based rural electrification [NEA, 2001]. Nepal is finalizing new policy framework for the rural electrification under the Tenth Five-Year National Plan (2003-2008). The rural electrification plan aims at providing electricity to 55 % of the Nepalese population [CADEC, 2003]. According to the National Planning Commission, 33 % of Nepal's population has access to electricity. CADEC, 2004 has recently published rural electrification status in Nepal, according to which about 2.33 % households have been electrified from renewable energy (micro-hydro and solar photovoltaic home systems). By the end of fiscal year (mid July 2003) about 31 % of households have been electrified together with national grid and small hydropower systems. The summary of the household electrified in Nepal through various sources is presented in Table 8.1.

Table 8.1: Summary on source of electricity and electrified households [CADEC, 2004]

Source of electricity	Percentage of households*
NEA and other isolated systems (domestic consumers)	29.83
Solar home system	1.02
Micro-hydro schemes	1.86
Non-domestic category of consumers of NEA and other systems	0.97
Not known (non-reported solar home systems, illegal connection)	5.71
Total reported by the 2001 Census	39.39

* Total households are 4,174,374. The average size of a household is ~5.4 [CBS, 2000]

The data on selected small renewable energy systems in Nepal are presented in Table 8.2.

Table 8.2: Installed number and capacity of small renewable energy technologies [CADEC, 2004]

<table>
<tr><th colspan="2">Source of electricity from small renewable energy technologies</th><th>Number of installation</th><th>Total capacity (kW)</th></tr>
<tr><td colspan="2">Solar home systems</td><td>42,550</td><td>1586</td></tr>
<tr><td rowspan="2">Micro-hydro electrification schemes</td><td>804 turbine mills (7,106.9 kW)</td><td rowspan="2">1,371</td><td rowspan="2">7,472</td></tr>
<tr><td>872 improved watermills (Pani-Ghatta),</td></tr>
<tr><td colspan="2">Biogas plants</td><td>111,395</td><td>766,147 m³</td></tr>
<tr><td colspan="2">Wind power plants (demonstration stand)</td><td>6</td><td>1.2</td></tr>
</table>

In 1990, the Government of Nepal adopted a liberal policy on the development of hydropower. It introduced Hydropower Development Policy in 1992. The Water Resources Act (1992), the Electricity Act (1992) and the Foreign Investment and

Technology Transfer Act 1991 played a decisive role to open possibilities for hydropower development through private sectors. As per SKAT/GTZ (1996) Nepal Electricity Authority has brought several small hydropower projects in pipeline under the Small Hydropower Master Plan (SHMP). However, financing of such projects has been the main bottle neck. Nepalese policy allocates about US$ 300,000 per annum budget for micro-hydropower development. Within this policy the Government of Nepal subsidizes up to 75 % on electrical equipment of micro-hydropower installation for remote regions.

8.4 Prospect for Small-hydro-based Decentralized Renewable Power System

Nepal has abundant hydropower potential. Her high gradient perennial rivers are capable of producing hydropower from few kilowatts to thousands of Megawatts. However, considering the technical, environmental and financial constraints, it is desirable to focus on the development of small-scale hydropower plants. Thousands of micro-hydro plants ranging from 1-50 kW have been installed and operated throughout the hilly and mountainous regions. The total installed capacity of these plants is around 5 MW. In tourist regions, such as Solukhumbu and Mustang districts, some VDCs have at least 3 to 6 micro-hydro plants located within a radius of 5-6 km. However, not all of these plants have the possibility to be interconnected with the powerful transmission lines in the remote regions. In such cases, a logical step would be to build a cluster of small-hydro-based decentralized renewable power systems (SHDRPS) each covering an area of 100-115 km² (see Figure 8.4) all over the country first and then gradually make them compatible to the regional grid.

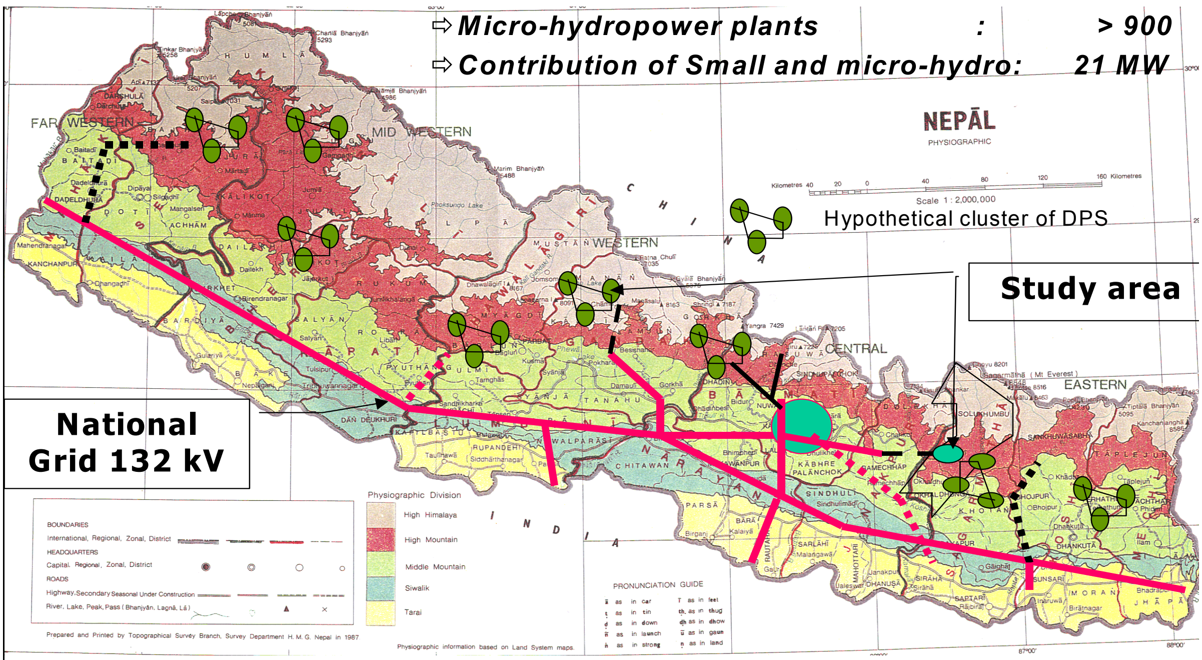
Although, micro-hydropower plants interconnected with the regional or national grid is a new technology in Nepal, there is a good prospect for its development. For example, the 100 kW Syange micro hydro plant in Western Development Region of Nepal is, probably, the first private plant to synchronise with the national grid (132 kV). Despite the technical and management difficulties, the interconnection plan of Mopun micro-hydro plant with 11 kV transmission line feed by Salleri-Chialsa Electric Company (SCECO) may be an innovative idea (refer Chapter 7). Tamrakar and Karki (2003) have also discussed the prospect for interconnecting a micro-hydropower plant on central grid of NEA in Kathmandu.

The concept of integrating micro-hydro with new RETs through isolated mini-grids in various mountainous regions of Nepal is an innovative concept. This concept facilitates a compact system design, reduces the system losses, and encourages local manufacturers and entrepreneurs and eases transportation difficulties. In combined operation, the system efficiency will be high. As a result, guaranteed cheap energy can be produced with better operational control. This concept is especially beneficial in the tourist regions.

There is also a prospect for integrating hydropower plants with other renewable energy technologies in Nepal. Nepal is also endowed with solar and wind energy potential. It has been reported that a total of 1100 kW peak Photovoltaic power system has been installed by various sectors in different parts of the country for rural electrification [CES, 2000].

Considering the current trend of Photovoltaic technology dissemination in Nepal, it may be assumed that this technology can play a significant role in rural electrification within a short period of time. Moreover, there are more than 25,000 Pani-Ghatta still in operation in Nepal. Their capacity could easily be upgraded to 1-3 kW for battery charging using locally available materials and skills. With a conservative estimate of 50 Watts per Household, 20 households in remote areas could potentially gain access to electricity from each Watermill-based Battery Charging Stations (WBCS).

Figure 8.2 presents a vision of the prospect for decentralized power system in Nepal.



Source: modified after NEA, 1998/99

Figure 8.2: Prospect for the development of DRPS for rural electrification

A study conducted by Dangrid Consult (1992) shows that about 500 GWh of electrical energy annually can be produced in the 12 km corridor from Kagbeni to Chhusang and has potential of 200 MW [Dangrid Consult in CES, 2000]. In fact, Nepal has already experienced the use of wind energy by installing two wind turbines each of 10 kW capacities in Kagbeni of Mustang district. Unfortunately, these wind turbines survived only for a few months due to unfavourable site conditions that were not considered in the design of the rotor and the tower. There are several potential sites for wind and solar power throughout the country, which can be promoted through the concept of JURE (refer Chapter 7). However, the lack of sufficient database and the costs of these technologies hinder their large scale exploitation.

The technology for producing electricity from biomass gasification and geothermal heat can also be included in the DRPS. Author also came to know electricity production from a 3 kW biomass-gasification pilot plant in Nepal [CES, 2000, RECAST, 1998]. However, these technologies have not been sufficiently studied in Nepal and they are not considered in this work.

The pace for electrification in Nepal and particularly in remote regions has been very slow. Even after four decades of rural electrification about 95 % of rural population is still living without electricity. Assuming that 60 % of total population residing in hills and mountains have to be electrified with the present Nepalese average electricity consumption of 22 kWh/capita per annum, a total of 262 GWh[12] electrical energy demand per annum is necessary. This energy is equivalent to a power demand of 150 MW at 20 % of load factor.

One of the main criteria for rural electrification is the people's willingness to pay (WTP) for the energy services. The WTP is a function of household income, education, health and the household size. Among these factors, the household income (HHINC) has the strongest influence on WTP. From a case study in Nayagaun of Kavre district of Nepal, where energy has been supplied through a micro-hydropower plant and several biogas plants, it has been found that for 1 % increase in HHINC there is a tendency to increase WTP by 6 % [Dhital et al, 2003]. Reliable electricity boosts up the income generation activities of the community. In Nepal, micro-hydropower plants running at 40 % of load factor are financially sustainable only when the rural people could contribute 7 % of their income for the purchase of electricity. Dhital et al (2003) conclude that the villagers are willing to spend even more than 15 % of their income for electricity if it were supplied reliably.

In order to encourage villager's entrepreneurship and to stop deforestation, the author assumes that the rural electrification must be oriented towards providing at least 120 Watt-hour per person per day of electrical energy. This makes the same power demand of 150 MW if the villagers were encouraged in using the daytime energy from stand-alone power plants to increase the load factor by 40 %. In Chapter 7 it has been shown that supply of electricity through a cluster of DRPS can easily achieve the load factor above 40 %.

Since the success of DRPS depends on various factors; mainly the technical and the financial, it is pre-requisite to implement DRPS at the beginning in the areas where a number of stand-alone power plants already exist close enough to be clustered and where there is a willingness to pay for the energy services. Based on the past rural electrification experience in Nepal, an annual electrical energy need of a tourist centre in hills and mountain regions can be safely taken as 0.5 GWh at the beginning of a project [Widmer and Arter, 1992]. There are more than 15 active tourist regions in hills and mountains of Nepal [SCECO, 2000]. Considering that there exist at least 2 tourist centres in each active tourist region, an annual electrical energy demand of 15 GWh can be estimated. This corresponds to a DRPS with an installed capacity of 4.3 MW at 40 % of load factor. Pandey (1995) estimates that to install 70 MW of micro- and mini hydro within 15 years, which can electrify almost all remote areas of hilly and mountainous regions, a total US$ 52.5 Million (average US$ 3.5 Million per annum at 1995 price basis) is required. The Government's budget to expand and strengthen the national grid is US$ 170 Million per annum. Only 2 % of this budget would be enough for rural electrification in remote regions.

[12] $0.87 \cdot 0.95 \cdot 0.60 \cdot 24\ \text{Mill. pop} \cdot 22\ \text{kWh per capita year} = 262\ \text{GWh}$

Nepal cannot afford another three decades to install this capacity. The Government of Nepal should, therefore, initiate effective strategy for the dissemination of DRPS [CETS, 1995].

8.5 DRPS in retrospect to the Renewable Energy Perspective Plan of Nepal

The Centre for Energy Studies has conducted a study on formulating **R**enewable **E**nergy **P**erspective **P**lan **o**f **N**epal (REPPON) for 2000-2020 [CES, 2000]. This study was guided by a need to maintain the supply diversity and to promote sustainable energy development in order to improve the quality of life in rural regions. This may also be interpreted as provision of phased transition of traditional rural energy systems towards modern and clean energy that supports growth, provide employment opportunities, and allows public and private sectors participation and ultimately helps reduce absolute poverty[13]. In this plan the renewable energy development has been considered as an integral part of other rural development activities.

REPPON also envisages the decentralization of planning, implementation and commercialisation of energy supply to meet development needs of the rural areas. It is believed that rural people as well as private sectors involved in the development of renewable energy technology are currently not equipped with required skill, knowledge and resources and call for government's interventions in the form of enabling programs for people and market through institutional, financial and technical supports.

REPPON estimates that by the end of 2020 at least 58 % of the rural population will be using at least one renewable energy technology under high growth rate (4.6% per annum) of energy consumption. This will increase the per capita energy consumption of rural population from 13.6 GJ to 21 GJ per annum. Among the other visions for the development of RETs in Nepal, REPPON's following two visions are directly supporting the present concept of developing DRPS in Nepal:

2. Decentralized energy system through active participation of stakeholders and
3. Development through market mechanisms.

In retrospect to REPPON, the concept of DRPS envisages a strategy for dealing effectively with the decentralized rural electrification to cover the energy need of the rural community in long-term and sustainable manner. On the other hand, the concept is based on the market mechanisms encouraging active participation of all stakeholders (public and private sectors). Further, the DRPS can help achieving the 5 goals envisaged in REPPON; and namely:

1. It ensures supply guarantee for meeting basic rural needs and reduce drudgery of women and children.
2. It creates opportunities for income generation and facilitates economic growth.

[13] World Energy Outlook (2002) defines the poverty line as a threshold of poverty of person having income of less than $2 per day. A person with earning less than $1 per day is defined as 'very poor'.

3. It encourages better education and awareness for minimum environmental impact on surroundings.
4. It decreases dependency on imported fuels through efficient and sustainable use of local energy resources.
5. It promotes local entrepreneurs in managing and operating RETs.

8.6 Three-tier Strategy for Rural Electrification through DRPS

For balanced regional development in the country, Nepal has been strategically divided, from East to West, into 5 developmental regions. These regions have been further divided into 14 zones with 75 district development committees (DDC), 3913 village development committees (VDC) and 58 municipalities. All of these regions cover three ecological belts (e.g., Mountain, Hill and Terai) from North to South (refer Figure 8.4 in page 108). The DDC and VDC are the major administrative units for coordinating and implementing the local development programmes. The lowest administrative unit is called ward consisting of several hamlets [Shrestha, 2000]. The strategy for rural electrification through DRPS as shown conceptually in Figure 8.2, which closely mimics the developmental philosophy of Nepal, is to support rural electrification at VDC level.

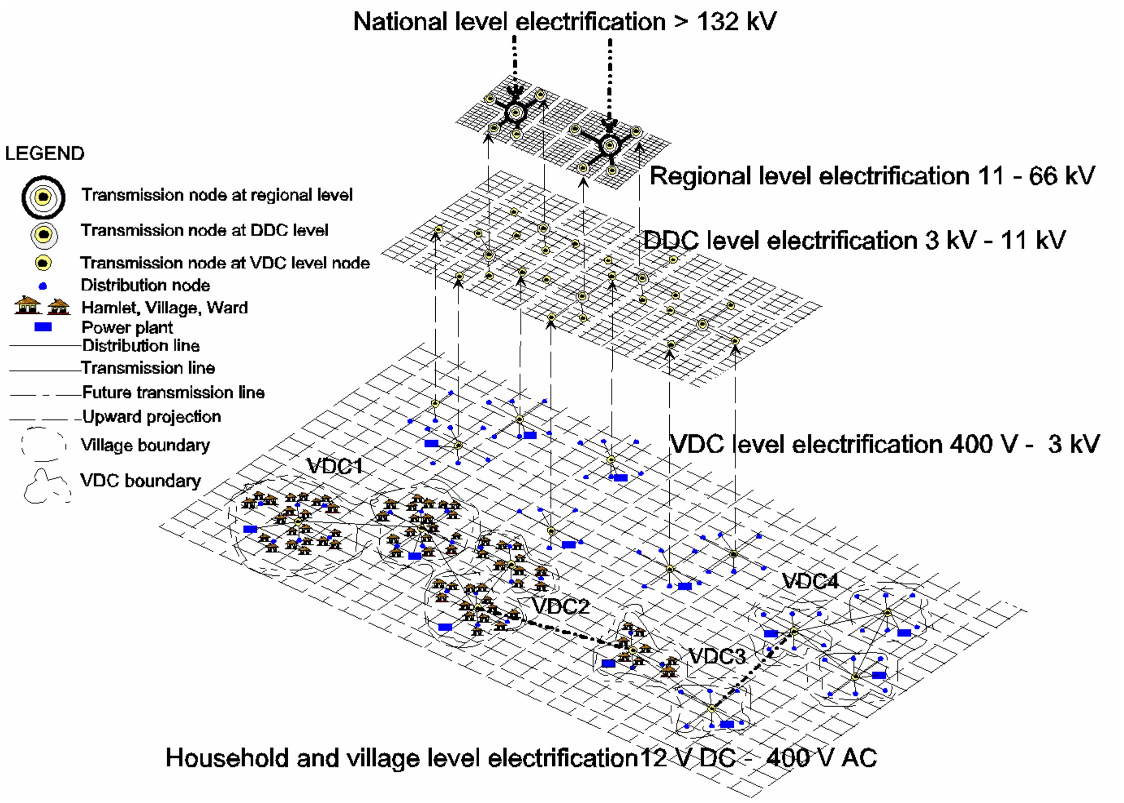


Figure 8.3: Three-tier rural electrification strategy. Also shown in the plan is the agglomeration process (clustering) of several VDCs level electrification through DRPS. [Maskey et al, 2003]

These strategies are described as follows:

1. **Household level electrification:** At this level, two groups for power demand must be differentiated:

   - **Individual household power demand:** This demand, which is mostly for lighting, radio, TV etc. ranging from few watts to 100W, should be covered through pico-scale electrical power system. The voltage level usually ranges from DC 12V to DC 48V. Usually a battery bank supported power systems are used. The solar-home systems are being most popular form for this range in rural regions of Nepal. There is also a huge potential for rehabilitation of watermills (Pani-ghatta) and upgrading them to charge batteries in Nepal.

   - **Group households power demand:** In addition to lighting, a group of households (Hamlets, wards) would require higher grade electricity for cooking, baking, machinery, communication, computer etc. ranging from 100 W to 5 kW. The voltage capacity of DPS can range from 48 V DC to three-phase 400 V AC type. At present, this demand in Nepal has been supplied partially either through pico-hydropower plants, the so-called Peltric set[14], or through photovoltaic plants with battery banks. Diesel generators have also been used in many parts of Nepal. The ITDG/Nepal is currently promoting electricity from wind turbines in this range, as known as wind home system (Rokaya 2002; personal communication at ITDG/Nepal).

   There is a good potentiality for combining all of these technologies, popularly known as hybrid power system, at this level. An experimental 900 W solar-wind hybrid system, which covers the electricity demand of a small tourist hotel, is known to exist in Nepal. Such a system with small energy storage facility saves expenditure on fuels or can retrofit completely fuel-fired generators. The owners of these systems could be potential suppliers of power if they were allowed to sell their surplus energy to grid. Once the household level DRPS is made compatible to local grid, the next logical step is to develop a mechanism for purchasing electricity from REEs by the owners of higher-level DRPS. Fortunately, Nepal has an institution to support mini-grid systems. Under the mini-grid support programme, the Alternative Energy Promotion Centre (AEPC) promotes mostly the single source distribution system [Thapa personal communication at AEPC, Nepal]. Except the NEA's grid system, there exists no mechanism for purchasing electricity from multiple power suppliers in isolated grid system. The AEPC could be encouraged to put this mechanism in its development portfolio.

2. **VDC & DDC level electrification:** To support economic activities of the rural population, this level of electrification demands power supply ranging form 5 kW to 1 MW. Within this range most of the VDC & DDC can be electrified.

[14] Peltric set, stands for a set of Pelton tubine coupled with the shaft of an induction motor as generator, is a most popular form of pico-type hydropower plant developed and manufactured in Nepal. Its generating capacity ranges form 1 kW-10 kW.

The voltage level can range from 3-phase 400 V to 11 kV. At present, this demand has been supplied either through government owned isolated small hydropower plants and photovoltaic power plants or privately owned mini/micro hydropower plants in Nepal. All of these plants are stand-alone type. Since many stand-alone small hydropower plants can be found located within a VDC or DDC, there is a high potentiality for interconnecting them with each other through a powerful low to medium voltage transmission lines (refer Chapter 5). RETs can also supplement such system. This integration allows the system to share the load proportionally to the capacity of diverse energy options. Small battery banks and deferrable loads are necessary components to stabilize the short-term power supply and demand fluctuations (Chapter 6). A community based REEs can be encouraged to venture in such level of DRPS. Alternatively, many independent power producers (IPP) active in developing small-scale hydropower plants in Nepal can be promoted to undertake the implementation of DRPS at this level.

3. **Regional level electrification:** Once the village level electrification through micro or mini-grid has been accomplished, the next logical step is to cluster them into single group and connect these ‘power clusters’ with the regional grid systems. The power range covered through this level is from 1 MW to 10 MW and the voltage level ranges from three-phase 11 kV to 66 kV. This system may require relatively large storage facilities (such as water reservoir or pumped storage) in order to cope with weekly or seasonal fluctuation in the power supply. In fact this level of electrification through national grid has been partially accomplished by the Nepal Electricity Authority under the Rural Electrification Programme. The Nepal Power System (NPS) with a voltage level of 132 kV extends East-West and connects all most all the regional headquarters of the developmental regions (See Figure 8.3).

Let us summarize the abovementioned three-tier strategy and classify DRPS according to the range of power and voltage demand of individual or a group of consumers and its purpose as given in Table 8.3 (refer Chapter 5):

Table 8.3: Classification of DRPS according to the different level of rural electrification need in Nepal

Type	Power demand	System voltage range and type	Level of electrification
Pico	< 100 W	12 V – 48 V (DC)	Individual household level
Micro	100 W – 1 kW	48 V (DC) – 1phase 230 V (AC)	Home electrification (Hamlet level)
Mini	1 kW – 5 kW	1 phase 230 V – 3 phase 400 V (AC)	Village grid (Village ward level)
Small	5 kW – 100 kW	3 phase 400 V – 3 kV (AC)	Micro-grid system (VDC level)
Medium	100 kW – 1 MW	3 phase 3 kV – 11 kV (AC)	Mini-grid system (DDC level)
Large	1 MW – 10 MW	3 phase 11 kV – 66 kV (AC)	Regional grid system (Zonal level)
Very large	> 10 MW	3 phase 66 kV – > 132 kV (AC)	National grid system (National level)

The advantage of this strategy is that it allows parallel implementation of rural electrification at all levels depending upon the availability of the resources and the power demand. Once the clustering of DPS is achieved under certain technical thresholds, the excess demand and supply can be exchanged within the DRPS network at all levels. This ensures the regional balance in electricity supply and demand.

As the DRPS includes all the actors of market mechanism such as power suppliers, transporters and end-users, it can also be modelled through economic system having spatial dimension. Unlike the other market goods, electricity is a commodity that must be consumed immediately after its production. However, some sort of short-term or long-term storage facilities must be included in the system in order to utilize energy resources rationally with respect to time and space. The DRPS can satisfy most of these criteria.

8.7 Proposed Pilot Project for Disseminating DRPS in Nepal

Background: A facility for research and development of decentralized renewable power systems is not available in Nepal. This has lead difficulties in supporting innovative ideas and lead to increased dependence on imported technologies. Author proposes to establish a pilot project for testing and disseminating decentralized renewable power systems elsewhere in Nepal with the aim to provide researchers and industries an opportunity to test commercially available as well as locally developed renewable power system's components. This project also aims at propagating its replicability and scalability to greater part of the country. This facility will provide universities a good base for research and development and will assist Nepalese industries to produce market ready decentralized renewable power systems.

Objectives: The decentralized renewable power systems test facility aims at meeting particularly the following objectives:

- To install and test hydro-turbines, water-wheels wind-turbines, photovoltaic and other components of a decentralized power systems
- To upgrade Watermill-based Battery Charging Stations
- To develop and test, in collaboration with industry, innovative concepts that improve performance and cost effectiveness of power system's components,
- To provide researchers and students possibility to work with complex systems and to provide training to Rural Energy Entrepreneurs (REEs).
- To provide national and foreign experts an environment to work under joint implementation program of the Kyoto-Agenda.

Scope: The facility will provide versatile and flexible environment for testing both real and simulated energy technologies based on renewable as well as conventional energy sources. A controllable load bank with both resistive and inductive components will be used to simulate village loads up to 50 kW in first phase and the capacity of this facility will be expanded gradually as the need arise. It will also provide controlled simulation of renewable energy sources.

The central control organ for simulation and testing will be the power dispatch centre, which will act as supervisory control mechanism for checking overall energy delivery and fuel consumption, power transients by simulating mechanical and electrical failures.

Target institution: Nepal has already well established governmental as well as non-governmental organisations for the development, promotion and dissemination of renewable energy technologies. The Alternative Energy Promotion Centre (AEPC) AEPC under ESAP supports mini-grid program with the aim to promote micro-hydro power supply to isolated and scattered settlements which are not connected to the national grid [AEPC, 2004]. Therefore, the author feels expedient to mention here that one of the 150 community based micro hydropower plant implemented through technical and financial assistance from REDP and AEPC respectively would be an ideal sites to implement such concept in its initial phase.

9 SUMMARY AND VISION FOR FURTHER RESEARCH

9.1 Summary

Energy is the key factor for achieving balance between society, economy and ecology and hence plays a vital role for sustainable development of any nation. Realizing this fact a consensus has been reached among scientists, engineers and economists as well as political communities all over the world that there is a need to supply energy for a growing population through public-private partnership without a detrimental impact on environment. Thus it has been suggested to use renewable energy resources as an alternative and shift gradually from non-renewable to renewable resources.

Rural electrification is a necessary element to support socio-economics of rural areas. Although it is important to electrify remote regions of developing countries rapidly, rural electrification must be implemented step-by-step (refer Chapter 1). It is suggested to implement rural electrification projects where there is a good market for them. As a first step, electricity should be provided reliably and affordably at the tourist centres, where the willingness to pay for it is high. In this way, it can stop deforestation, help to expand rural employment and stop migration to urban areas. Consequently, these electrified tourist centres serve as demonstration sites to encourage neighbouring villages to successively replicate rural electrification.

Although the renewable energy resources are freely available and indigenous in every country, they are highly dependent on local hydro-meteorological conditions. Moreover, the power density of wind and solar energy resources is very low as compared to hydro energy that makes the energy cost from wind and photovoltaic technologies expensive. An investment in technology based purely on wind and solar energy resources is still risky to both private entrepreneurs and governments of developing countries. Despite the fact, that some renewable energy technologies (RETs) such as micro-hydropower, small wind, biogas, and solar home systems are popular and have been proved to be an appropriate technology in the rural regions of developing countries, a lot of problems are to be solved for rapid dissemination of such technologies. The main problem is that a single-source and stand-alone RETs are over dimensioned and have very low load factors. Furthermore, they do not provide flexibility and reliability of the power supply.

To reduce these disadvantages and to utilize RETs on a commercial basis, small scale power systems using wind and solar energy with diesel and or batteries, as known as “hybrid systems”, have been developed during the last two decades. On the other hand, small hydropower due to its comparably high power density and fairly stable supply proves to be the superior candidate for the combined operation in large scale decentralized power systems.

Due to the economy of scale and stochastic hydrology, a run-of-the river type hydropower plant approaches its economic limits with increasing size, beyond which the unit production cost will be too high. So it is not economical to increase the design discharge or plant capacity beyond that limit (refer Chapter 1).

To supply the need for supplemental power to a small power network it may be expedient to look for other renewable alternatives such as photovoltaic or wind power plants. Because of the fluctuating power supply, these alternatives have a very poor load dispatching ability without energy storage facility. Therefore, an energy storage device must be integrated in the system. Thus hydropower plant takes the base and intermediate load regions of a load-duration curve and the energy storage facility takes the peak load regions (refer Chapter 3).Hence, where hydropower potential exists, there is a need for a gradual transformation from single source RETs to hydropower plant based multi-sources RETs in order to avoid the disadvantages inherent in these technologies. The author therefore proposes to develop small-hydro-based decentralized renewable power systems (SHBDRPS).

The concept of SHBDRPS discussed in Chapter 1 may be useful for understanding the advantage of such a system for rural electrification. It may guarantee the power supply and may increase the operational flexibility. Being modular in nature, SHBDRPS can reduce the investment cost by gradually implementing them, as the demand grows. Its operation and maintenance cost are very low as compared to thermal power plants and hence it improves the life cycle cost (LCC). However, the combined operation increases the complexity of rural electrification in developing countries.

There is a need for a planning tool that facilitates quick determination of an optimum size of SHBDRPS. In this work, a comprehensive research on state-of-the-art (refer Chapter 2) was carried out to identify the research gap and to develop not only the planning tool but also to suggest the process of institutional development for SHBDRPS particularly in a Nepalese prospect (refer Chapter 8).

The concept of SHBDRPS is innovative. It facilitates a compact system design, reduces the system losses and encourages local entrepreneurs in economic activities. This concept is also oriented towards retaining the existing Rural Energy Entrepreneurs (REEs) and attracting new ones. The three-tier strategies for electrification through SHBDRPS closely follow the developmental philosophy of Nepal and are ‘in line’ with the vision of Renewable Energy Perspective Plan of Nepal (REPPON; refer section 8.6). Since it allows parallel implementation at all levels of rural electrification, it can be planned well in advance depending upon the resources and time available.

The essential feature of the developed tool is that it utilizes the interdependencies of various factors on a functional basis. This is due to the fact that at preliminary project development stage many data are not readily available. Data has to be either guessed or estimated by using standard graphs and tables. For the rapid system analysis it is not advantageous to utilize such methods, which are time consuming and expensive. On the other hand, many mathematical and empirical formulas are readily available, which could be advantageously used. Therefore, the present tool utilizes the normalized (theoretical) load-duration curve method developed by Rossander (1913), which has been discussed in Chapter 3.1.1. Based on only three parameters of a system load, namely minimum, average, maximum load, a whole range of load scenarios can be developed quickly and effectively. Derivation of this equation is presented in Appendix I.

In analogy to this method, the author suggests to utilize Equation A.16 for developing flow-duration curves (refer Appendix I).

Based on these theoretical curves, the present tool is capable of generating essential input on consumers load data and energy source data if the minimum, average and maximum values of any time dependent variables are available (In this case the discharge and the consumer's load). It is expedient to note that Mosonyi (1948) also proposed a theoretical flow duration curve (refer Equation A.15) for the hydrological design of large reservoirs. The fundamental difference between the Equation A.15 and A.16 (refer Appendix I) is that the former uses a fixed numerical exponent, whereas the later uses variables derived from three input parameters, which reduces again the use of tabular data. Further, the author examined the calculated flow-duration curve against the actual data from Heldung river in Nepal (refer Figure A-4 in Appendix I). The result is very promising.

Another important feature of the present work is the thorough analysis of cost-function based on an empirical cost formula (refer Equation 4.4 in Chapter 4) suggested primarily by Gordon (1979, 1983). Based on the cost data from Nepalese hydropower projects ranging from 1 kW to 10 MW, and comparing them with the data published by Gordon (refer Table 4.5 in Chapter 4), the author determined the k-values as a function of head and power for pico, micro, mini and small hydropower projects (refer Table 4.5) suitable for Nepalese conditions. At present only the cost-function for total initial cost of hydropower is modelled. However, for the full development of the present tool, it is essential to find k-values for other components of power systems as well. Some ideas for this may be drawn from the cost-functions for hydropower components summarized in Table 4.4 in Chapter 4. Moreover, the cost-function for other components of decentralized power systems namely, wind, photovoltaic, and battery bank is based on the specific-cost method. The cost-function for the transmission line is taken from the standard of developed countries. Its utilization for developing countries should be examined further.

The present work is dedicated to transfer the well established scientific and engineering knowledge on power system development and economics for the rational utilization of renewable energy technologies in the remote regions of developing countries. The developed tool is aimed at attacking problems even if the situation does not permit to collect all essential information before a project is developed. This saves a huge amount of time and resources during the planning phase. Consequently, the developed tool shortens the decision making process and project implementation phases. In this sense the present work is basically innovative.

The outcome of this tool may also be useful for professional training and experimentation. The discussions in Chapter 3 to 6 are therefore indispensable to describe the mechanisms of the developed tool. It should also serve to explain the functionality of the developed tool and hence to use it as guideline for understanding the model code. During the literature survey it was revealed that the optimisation process using mathematical as well as other heuristics and on Evolutionary theory based methods has been well developed (refer Chapter 2). It was found that the simulation procedure for isolated mini-grid incorporating different renewable energy technologies, which depends on the project's case-to–case basis, was not sufficiently addressed.

Therefore, the author found it challenging to focus his effort on modelling the simulation procedure for a small hydropower based power system in such a way that it also allows simulation as well as optimisation using standard commercially available optimisation tools. Chapter 6 is dedicated to explain the algorithm based on the power and energy balance method. Hence, the dispatching strategy shown in Figure 6.3 is the central novelty of the planning tool developed in the present work. This tool is named here as Decentralized Power System Simulation and Optimisation Model (DEPSO). The DEPSO model (see Figure 5.5) consists of the following 10 modules:

1. Energy data analysis module
2. System configuration module
3. Hydropower plant module
4. Photovoltaic plant module
5. Wind power plant module
6. Mini-grid module
7. Load analysis module
8. Economic analysis module
9. Power and energy balance module
10. Power system optimisation module

For the model validation, the data published by RETScreen® International (2004) has been used. Table 5.9 summarizes the actual data of the Brown Lake Hydro Project in British Columbia, Canada as well as the simulated data. The efficiency curves of both actual and simulated turbines were compared in Figure 5.15, which shows a fairly acceptable correlation coefficient of $R^2 = 0.63$. The reason for some discrepancy is also thoroughly discussed in section 5.5.3.7. The Model capacity was verified by plotting the performance curves as shown in Figure 5.16. A flow-duration curve of $Q_{d, 35\%}$ simulated by the model fairly matches with the flow-duration curve used by the turbine manufacturer for the efficiency test as given in Table 5.9. The power and head duration curves for a 72 % plant factor are also shown. Similarly, for the sensitivity analysis of a load dependent power system it is necessary to check the performance of hydropower plants on various plant factors. Figure 5.17 depicts an example of the effect of 40 % plant factor on the power production as well as the efficiency.

The flow charts presented in Figure 5.10 for the hydropower plant module, Figure 5.20 for the wind power plant module, and Figure 5.24 for the photovoltaic plant module serve as the guide-line for data input and user's interface. Finally, the mini-grid and the power and energy balance modules are thoroughly discussed in section 5.5.6 and 6.2 respectively. The power flow equation for the mini-grid (see Figure 5.29) is explained using the case study of Junbesi rural electrification (JURE), which is presented in Chapter 7. The solution of the equation 5.72 is found using Gaussian elimination method. The input data for this calculation is summarised in Appendix II.

Similarly, the construction of the power system simulation and optimisation model is presented in Chapter 6. Figure 6.1 depicts schematically the components of the simulation model. Subsequently the classification of loads is discussed in section 6.4.2.

The power and energy balance algorithm presented in section 6.3 and summarised in Figure 6.3 is basically designed for the parallel iteration process required for the simulation and optimisation the power system's components in each designed time step. Further, a detail power dispatch strategy is discussed and summarized in Tables 6.1 to 6.6. The developed tool allows optimisation of systems parameters as decision variables using one of the following objective functions at a time:

1 Minimize the life-cycle cost
2 Minimize the cost of energy
3 Maximize the system efficiency
4 Maximize the net present value

The decision variables that can be simulated and optimised using hard and soft boundary conditions are presented in Table 6.7. Hard boundary conditions, which are presented in Table 6.8, are both necessary and sufficient and must be fulfilled during the simulation and optimisation process. In fact these boundary conditions are used to develop the power dispatch strategy. The soft boundary conditions presented in Table 6.9 are required to check the simulated size of individual components. They are important but not necessary conditions for the optimal system configuration. Their use increases the search space for optimisation and therefore used only when design of optimised parameters are required. At present the soft boundary conditions are modelled only for hydropower components. The developed tool is capable to provide necessary technical as well as economic parameters (see Table 6.10) both analytically and graphically required for decision making. Finally the present model also allows performing sensitivity analysis of the optimised project parameters according to various demand and supply scenarios (refer Table 6.11). For each scenario the sensitivity analysis is performed under the three categories; namely: base, pessimistic and optimistic cases.

The application of the developed concept and tool for rapid analysis of rural electrification alternatives has been demonstrated and discussed thoroughly in Chapter 7. The results of the case study are presented in Appendices II. The success of DRPS depends mainly on the technical and the financial factors. Therefore, its development should be considered in the areas where a number of stand-alone power plants already exist sufficiently close enough to be clustered effectively. Based on the hypothetical case study of Junbesi rural electrification (JURE), it may be concluded that a cluster of small-scale hydro-plants based DRPS covering an area of 100-115 km² for a voltage level of 3 kV is optimal and may be replicated throughout the remote regions of developing countries having similar boundary conditions. Such a cluster of DRPS can then be easily interconnected with the regional grid under three-tier strategy discussed in Chapter 8.

Chapter 8 aimed at providing the prospect for small hydropower plant based decentralized renewable power system (SHBDRPS) in developing countries taking the case study of Nepal's rural electrification policy. Since the motivation to conceptualise the objectives of the present work was based on the rural electrification experience from Nepal, this chapter should be looked as epilogue. Analysing the energy options and status of rural electrification policy of Nepal this chapter deals with the prospect for small-hydro-based DRPS and derives the three-tier strategy for the rural electrification through DRPS concept. In retrospect to

Renewable Energy Perspective Plan of Nepal (REPPON), the concept of DRPS is 'In line' with the two visions and the five goals set under this plan (refer section 8.6). Finally, this chapter is also dedicated to propose to establish a pilot project for testing and promoting DRPS in Nepal.

The importance of DRPS for rural electrification has been demonstrated. Comparing the electricity prices from national grid of Nepal and stand-alone hydro plants, the electricity price from small-hydro-based decentralized renewable power system (SHBDRPS) is cheaper. Eventually, the rural electricity consumers as well as the REEs will be encouraged to maintain the operational and financial conditions of the plants. For a complex system like SHBDRPS, the system efficiency also known here as performance index (PI) together with the cost of energy (COE) and the plant utilization factor play a decisive role for decision-making. However, a sensitivity analysis is indispensable for checking the stability and the reliability of the result. The present planning tool is capable of performing sensitivity analysis quickly and effectively.

The success of DRPS depends mainly on the technical and financial factors. Therefore the development of DRPS should be considered in areas, where already several isolated power stations exist, which stand close enough together to be able to effectively united. Based on the hypothetical case study of the rural electrification of Junbesi rural electrification (JURE) one can arrive to the conclusion that a cluster of small hydropower plants on DRPS basis, which covers a surface area of 100-115 km^2, on a high-tension level of 3kV is optimal and could find application in other remote regions where similar boundary conditions exist. Such cluster of DRPS can be connected easily with regional electricity mains. The use of the developed concept and the tool to the fast analysis of rural electrification alternatives has been demonstrated in Chapter 7). The results of the case study are represented in the appendices II.

9.2 Vision for Further Research

The present work was aimed at making the planning tool for SHBDRPS as versatile as possible incorporating all the planning and design concepts and knowledge based mechanisms required by engineers and decision makers. Therefore, this work heavily draws a lot of well known concepts and formulations that have been accepted by engineering and economic communities for the development of a project. However, with consideration of the time and efforts that such an ambitious project needs, it may be concluded that the present work has laid only a foundation stone for further improvement of the model. One of the essential concepts of the developed model is the dispatching strategy, based on which it is possible to perform power and energy balance calculation using a computer (refer Chapter 6). The author hopes that this strategy may lead to the development of electronic power controllers for decentralized renewable power systems. Further, determination of k-values in the cost-functions for system components are needed to be further worked out for its general applicability. Similarly, it may also be possible to develop algorithms for modelling each component of a power system [Lubosny, (2003)] (e.g., turbine, generators, power controller etc.), which would be the future work for the full development of the present tool.

Clustering of DRPS throughout the country is an expensive and time consuming exercise. It is highly dependent on the spatial distribution of potential sites for power supply and demand. It should also be noted here that simulation and optimisation processes of a SHBDRPS will be more powerful once combined with geospatial coordinates of a site. Therefore, it has been realized that there is a need to integrate the developed model with widely utilized software such as Geographic Information Systems (GIS). With the rapid development of information technologies and the geographic positioning system (GPS), the author also visualizes the integration of the present simulation and optimisation model with these technologies in near future. Similarly, the Matlab-based Simulink® program could also be used for rapid prototyping of decentralized power systems. The complexity of simulation algorithms requiring a large number of sophisticated equations, a holistic planning tool for a power system analysis is yet to be developed. It is hoped that this gap will also be filled in near future. Therefore, the author concludes that an integration of the present model developed for simulation and optimisation of small hydropower based decentralized renewable power systems with the commercially available software is the necessary future work to be conducted for the rapid rural electrification appraisal.

10 ZUSAMMENFASSUNG UND AUSBLICK

10.1 ZUSAMMENFASSUNG

Weil man festgestellt hat, dass Energie der Schlüsselfaktor für nachhaltige Entwicklung ist, gelangte man unter Wissenschaftlern, Ingenieuren, Wirtschaftswissenschaftlern und politischen Vereinigungen auf der ganzen Welt zu der Übereinkunft, dass es notwendig ist, die wachsende Bevölkerung ohne nachteilige Auswirkung auf die Umwelt mit Energie zu versorgen. Daher wurde als Alternative vorgeschlagen, erneuerbare Energiequellen zu nutzen und schrittweise von nicht-erneuerbaren auf erneuerbare Energiequellen umzusteigen. Obwohl die erneuerbaren Energiequellen frei erhältlich und in allen Ländern zu finden sind, sind sie in Bezug auf Zeit und Raum stochastisch und in hohem Maße von lokalen Wetterbedingungen abhängig. Außerdem ist die Energiedichte von Wind- und Solarenergiequellen sehr niedrig, was letztlich zu hohen Energiekosten führt. Für private Unternehmer ist eine Investition in Technologie, die nur auf Wind- und Solarenergiequellen basiert, in Entwicklungsländern immer noch riskant. Trotz der Tatsache, dass einige Technologien zur Nutzung erneuerbarer Energie(RET, *renewable energy technologies*), wie beispielsweise Wasserkraft-, Kleinwindkraft-, Biogas- und Solarheimsysteme verbreitet sind und sich als passende Technologie in ländlichen Regionen von Entwicklungsländern erwiesen haben, gibt es viele Probleme, die für deren schnellen Einsatz gelöst werden müssen. Das Hauptproblem besteht darin, dass ein Einzelenergie-RET-System überdimensioniert ist und einen geringen Lastfaktor hat, es bietet keine flexible und zuverlässige Stromversorgung.

Um den Einfluss dieser Nachteile zu verringern und RET-Systeme gewerblich nutzen zu können, ist im letzten Jahrzehnt ein klein dimensioniertes Stromerzeugungssystem, ein sogenanntes Hybridsystem, das Wind- und Solarenergie in Verbindung mit Diesel und/oder Batterien nutzt, vor allem als Erweiterung zu den Dieselgeneratoren und zur Kraftstoffschonung entwickelt worden. Die Kleinwasserkraft hat sich andererseits wegen ihrer vergleichsweise hohen Leistungsdichte und ihrer relativ stabilen Versorgung als Favorit für den Verbundbetrieb von groß dimensionierten Stromversorgungssystemen herausgestellt. Aus wirtschaftlichen Gründen in Bezug auf Größenordnung und stochastischer Hydrologie erreicht ein Flusskraftwerk mit zunehmender Größe seine wirtschaftliche Obergrenze, über der die Produktionskosten zu hoch sind. Deshalb wäre es nicht wirtschaftlich, den Ausbaudurchfluss oder die Kraftwerkskapazität über diesem Limit zu erhöhen. Um den Zusatzbedarf des Stromnetzes decken zu können, wäre es zweckmäßig, sich nach anderen erneuerbaren Alternativen umzusehen, wie Photovoltaik- oder Windkraftwerken. Weil sie nur eine stark variierende Energieversorgung zulassen, sind sie ohne Speichermöglichkeit nur in geringem Maße dazu fähig, die Last dynamisch zu verteilen. Deshalb ist für ein solches integriertes System ein Energiespeichergerät unbedingt nötig. So deckt ein Wasserkraftwerk die Grund- und Mittellastbereiche einer Last-Dauer-Kurve und das Energiespeichergerät die Spitzenabschnitte der Last ab(siehe Kapitel 3 und 5).

Deswegen müsste man, wo es Wasserkraftpotential gibt, schrittweise von Einzelenergie-RET-Systemen auf wasserkraftwerk-basierte Mehrenergie-RET-Systeme umsteigen, um die Nachteile der anderen Technologien zu umgehen. Der Autor schlägt daher ein auf Kleinwasserkraftwerken basiertes dezentrales Stromerzeugungssystem(HBDPS, *hydroplants based decentralized power system*) vor.

Das HBDPS-Konzept, das in Kapitel 1 erörtert wurde, könnte für das Verständnis des Vorteils eines solchen Systems für die ländliche Elektrifizierung nützlich sein. Solch ein System könnte die Stromversorgung garantieren und die Betriebsflexibilität erhöhen. Weil sie naturgemäß modular sind, können HBDPS-Systeme die Investitionskosten senken, indem man mehrere von diesen realisiert, sobald die Nachfrage steigt. Die Betriebs- und Erhaltungskosten sind im Vergleich zu brennstoffbetriebenen Kraftwerken sehr gering und verbessern somit die Lebenszykluskosten. Aber der Verbundbetrieb erhöht auch die Komplexität der ländlichen Elektrifizierung in Entwicklungsländern. Daher bräuchte man ein Planungswerkzeug, das die schnelle Einrichtung eines HBDPS-Systems mit optimaler Größe ermöglicht. Bei dieser Arbeit wurden umfangreiche Nachforschungen angestellt, um die Forschungslücken zu identifizieren, die Planungsmechanismen zu entwickeln, und auch den Prozess einer institutionellen Entwicklung von HBDPS-Systemen besonders in Hinsicht auf Nepal vorschlagen zu können(siehe Kapitel 8).

Ländliche Elektrifizierung ist ein notwendiges Element, um die Sozioökonomie ländlicher Gebiete zu unterstützen. Obwohl es wichtig ist, abgelegene Regionen in Entwicklungsländern zu elektrifizieren, muss die ländliche Elektrifizierung schrittweise erfolgen. Es wird daher auch vorgeschlagen, die ländliche Elektrifizierung dort einzusetzen, wo ein guter Absatzmarkt dafür besteht. Als erster Schritt sollte die Elektrizität zuverlässig und kostengünstig - im Fall von Nepal - an ländlichen Touristikzentren angeboten werden. Auf diese Weise kann man die Abholzung stoppen, helfen, die Beschäftigung der ländlichen Bevölkerung zu steigern, und so die Migration in städtische Gebiete aufhalten. Diese elektrifizierten Touristikzentren können als Vorführungsmodelle dienen, um Nachbardörfern einen Anreiz zur schrittweisen Elektrifizierung zu geben.

Das HBDPS-System ist eine Neuerung, weil es einen kompakten Systemaufbau ermöglicht, die Systemverluste verringert, und lokale Investoren zu wirtschaftlichen Unternehmungen ermutigt. Dieses Konzept orientiert sich auch daran, bestehende ländliche Stromversorgungsunternehmer(REE, *rural energy entrepreneurs*) dazubehalten und die Anziehung neuer zu begünstigen. Die Drei-Schichten-Strategie zur Elektrifizierung durch HBDPS-Systeme halten sich an die Entwicklungsphilosophie Nepals und liegen nahe bei der Vision von REPPON(*renewable energy perspective plan of Nepal*). Weil sie den parallelen Einsatz auf allen Niveaus ländlicher Elektrifizierung erlauben, können sie gut im voraus geplant werden, je nachdem, welche Ressourcen und wie viel Zeit zur Verfügung stehen.

Das Hauptmerkmal des entwickelten Werkzeugs ist die Verwendung der Wechselbeziehung von verschiedenen Faktoren auf einer funktionalen Basis. Dies geschieht aufgrund der Tatsache, dass bei der Vorbereitungsphase der Projektentwicklung viele Daten nicht bereitstehen. Die Daten müssen entweder erraten oder unter Benutzung von Standardgraphen oder Tabellen abgeschätzt werden. Für die schnelle Systemanalyse ist es nicht vorteilhaft solche Methoden zu verwenden, weil sie zeitaufwendig und teuer sind. Andererseits stehen viele mathematische und empirische Formeln bereit, die vorteilhaft angewendet werden können. Das derzeitige Werkzeug benutzt daher die Methode der normalisierten (theoretischen) Last-Dauer-Kurve, die von Rossander(1913) entwickelt wurde und die in Kapitel 3 erörtert wird(siehe Gleichung 3.25). Aufbauend auf nur drei Parametern einer Systemlast, nämlich Minimal-, Durchschnitts- und Maximallast, kann ein ganzes Spektrum an Last-Szenarien sehr schnell und effektiv entwickelt werden. In Analogie zu dieser Methode schlägt der Autor vor, Gleichung 3.28 zur Entwicklung von Abfluss-Dauer-Kurven zu benutzen. Dadurch, dass das derzeitige Werkzeug auf diesen theoretischen Kurven basiert, ist es in der Lage die notwendige Eingabe von Verbraucherlastdaten und Daten der Energiequelle zu generieren, wenn das Minimum, der Durchschnitt und das Maximum beliebiger zeitabhängiger Variablen zur Verfügung stehen, in diesem Fall der Abfluss und die Verbraucherlast. Man sollte beachten, dass Mosonyi (1948) auch eine theoretische Last-Dauer-Kurve für den hydrologischen Entwurf von großen Reservoirs vorschlug(siehe Gleichung 3.27). Der entscheidende Unterschied zwischen den Gleichungen 3.27 und 3.28 ist, dass die frühere einen festen numerischen Exponenten verwendet, während die spätere Variablen von drei Eingabedatenmengen abgeleitet werden, was wiederum die Verwendung von Tabellendaten verringert. Weiterhin untersuchte der Autor die berechnete Fluss-Dauer-Kurve an gegenwärtigen Daten des Flusses Heldung in Nepal(siehe Abbildung 3.7). Das Ergebnis ist sehr vielversprechend.

Ein weiteres wichtiges Merkmal der vorliegenden Arbeit ist die gründliche Analyse der Kostenfunktion, die auf einer empirischen Kostenfunktion basiert(siehe Gleichung 4.4) und primär von Gordon (1979, 1983) eingeführt wurde. Aufbauend auf den Kostendaten nepalesischer Wasserkraftanlagen, die von 1kW bis 10MW reichen, und dem Vergleich dieser mit den von Gordon veröffentlichten Daten, untersuchte der Autor die k-Werte als Funktion der Fallhöhe und der Leistung von Piko-, Mikro-, Mini- und Kleinwasserkraftprojekten(siehe Tabelle 4.5), angepasst an nepalesische Bedingungen. Gegenwärtig wird nur die Kostenfunktion für die gesamten Anfangskosten der Wasserkraft modelliert. Aber für die vollständige Entwicklung des gegenwärtigen Werkzeugs ist es wesentlich, auch für die anderen Komponenten des Stromerzeugungssystems k-Werte zu finden. Einige Ideen hierfür könnten aus den Kostenfunktionen für Wasserkraftkomponenten abgeleitet werden, welche in Tabelle 4.4 zusammengefasst sind. Weiterhin basiert die Kostenfunktion für andere Komponenten eines dezentralen Stromerzeugungssystems, nämlich Wind, Photovoltaik und Batterien auf der spezifische-Kosten-Methode. Die Kostenfunktion für die Überlandleitung basiert auf dem Standard von Entwicklungsländern. Ihre Nutzung für Entwicklungsländer sollte noch weiter untersucht werden.

Die vorliegende Arbeit widmet sich der schnellen und effektiven Übertragung bewährten wissenschaftlichen und ingenieurtechnischen Wissens über die Entwicklung und Wirtschaftlichkeit von Stromerzeugungssystemen in die Praxis. Der

Autor konzentrierte daher seine Anstrengungen auf die Modellierung dieser Kenntnisse für die vernünftige Anwendbarkeit von Technologien zur Nutzung erneuerbarer Energie in abgelegenen Regionen von Entwicklungsländern. Das entwickelte Werkzeug zielt auf das Angehen von Problemen ab, auch wenn die Situation es nicht zulässt, alle notwendigen Informationen vor der Entwicklung eines Projektes zu sammeln. Das spart eine große Menge an Zeit und Geld während des Planungsprozesses ein. Folglich verkürzt das entwickelte Werkzeug den Entscheidungsfindungsprozess und die Phasen der Projektrealisierung. In diesem Sinn kann die vorliegende Arbeit als Neuerung angesehen werden. Das Ergebnis wie es in der Zielsetzung(siehe Kapitel 1) der vorliegenden Arbeit vorgestellt wurde, könnte auch Einsatz für berufliche Weiterbildung und berufliches Experimentieren finden.

Die Diskussionen in Kapitel 3 und 5 waren daher notwendig, um die Mechanismen des entwickelten Werkzeugs zu beschreiben. Sie sollten auch dazu dienen, die Wirkungsweise des entwickelten Werkzeugs zu erklären und sie so als Richtlinien für das Verständnis des Modellcodes bei dessen Anwendern einzusetzen. Beim Studium der Fachliteratur, stellte sich heraus, dass der Optimierungsprozess recht gut unter Verwendung von mathematischen, heuristischen und auf der Evolutionstheorie basierenden Methoden, die teils standardmäßig, teils kommerziell erhältlich sind, entwickelt wurde. Was fehlt ist eine Ausarbeitung der Simulationsprozedur, die bei Projekten von Fall zu Fall anders ist und die sich daher nicht einfach standardisieren lässt. Daher sah der Autor eine Herausforderung darin, seine Bemühungen so auf die Modellierung der Simulationsprozedur für ein auf Kleinwasserkraftwerken basiertes Stromerzeugungssystem zu richten, dass sie auch die Optimierung durch ein standard-kommerziell erhältliches Optimierungswerkzeug erlaubt. Kapitel 6 beschäftigt sich mit der Erklärung des Algorithmus, der auf der Leistungs- und Energieausgleichsmethode basiert. Daher ist in der vorliegenden Arbeit die Verteilungsstrategie, wie sie in Abbildung 6.3 dargestellt ist, die zentrale Neuerung des Planungswerkzeugs, des sogenannten Dezentralen Kraftwerk-Simulations- und Optimierungsmodells(DESPO, *decentralized power system simulation and optimisation model*). Das DESPO-Modell (siehe Abbildung 5.5) besteht aus den folgenden 9 Modulen:

1. Energiedatenanalysierungsmodul
2. Systemkonfigurationsmodul
3. Wasserkraftwerkmodul
4. Photovoltaikkraftwerkmodul
5. Windkraftwerkmodul
6. Mininetz-Modul
7. Lastanalysierungsmodul
8. Wirtschaftlichkeitsanalysierungsmodul
9. Leistung-Energie-Ausgleichsmodul

Die Turbinenauswahl und die Bestimmung ihres Durchmessers wurde auf dem Algorithmus, der von Giesecke und Mosonyi(2003) vorgeschlagen wurde, aufgebaut, während der Wirkungsgrad aus gewählter Turbinen durch die Verwendung von veränderten Formeln nach RETScreen® International(2004) bestimmt wurde.

Für die Überprüfung der Richtigkeit des Modells wurden die Daten, die von RETScreen® International(2004) veröffentlicht wurden, benutzt. Tabelle 5.9 fasst die momentanen Daten des Brown-Lake-Hydroprojektes in British Columbia(Kanada) und die simulierten Daten zusammen. Die Effizienzkurven der tatsächlichen und der simulierten Turbinen wurden in Abbildung 5.15 verglichen, welche einen recht guten Korrelationskoeffizienten von R^2=0.63 zeigt. Der Grund für eine gewisse Abweichung wurde ebenfalls gründlich auf Seite 85 diskutiert.

Die Leistungsfähigkeit des Modells wurde bestätigt, indem Leistungsverhaltenskurven wie sie in Abbildung 5.16 dargestellt sind angefertigt wurden. Eine Abfluss-Dauer-Kurve von $Q_{d,\ 35\%}$ wie sie in dem Modell simuliert wurden stimmt recht gut mit der Abfluss-Dauer-Kurve, die vom Turbinenhersteller für den Effizienztest benutzt werden, wie in Tabelle 5.9 gezeigt überein. Die Leistung und die Fallhöhe-Dauer-Kurven für einen Kraftwerkfaktor von 72% werden ebenso dargestellt. Ähnlich ist es für die Empfindlichkeitsanalyse eines lastabhängigen Kraftwerks notwendig, das Leistungsverhalten von Wasserkraftwerken bei verschiedenen Kraftwerkfaktoren zu prüfen. Abbildung 5.17 stellt ein Beispiel der Auswirkung von 40% Kraftwerkfaktor auf die Stromerzeugung und die Effizienz dar.

Die Flussdiagramme für das Wasserkraftwerkmodul sind in Abbildung 5.10 auf Seite 73, für das Windkraftwerkmodul in Abbildung 5.20 auf Seite 91 und für Photovoltaikkraftwerke in Abbildung 5.24 auf Seite 98 dargestellt. Vom Autor entwickelt dienen sie als Richtlinien für Dateneingabe und die Anwenderschnittstelle. Schließlich werden das Mini-Netz- und das Leistung-Energie-Ausgleichsmodul gründlich erörtert.

Die Wichtigkeit von DPS für die ländliche Elektrifizierung wurde demonstriert. Durch den Vergleich der Elektrizitätspreise vom zentralen nepalesischen Netz und der isolierten Wasserkraftwerke wird klar, dass der Preis von DPS sehr viel niedriger ist. Letztendlich werden die ländlichen Elektrizitätsverbraucher und die REE dazu ermutigt, die Betriebs- und Finanzbedingungen der Kraftwerke aufrechtzuerhalten. Für ein so komplexes System wie DPS, spielen die Systemeffizienz - hier auch bekannt als Performanceindex(PI), die Kosten pro Energie(COE) und der Kraftwerknutzungsfaktor eine entscheidende Rolle für die Entscheidungsfindung. Aber eine Empfindlichkeitsanalyse ist unverzichtbar, um die Stabilität und die Zuverlässigkeit des Ergebnisses zu überprüfen. Das derzeitige Planungswerkzeug ist in der Lage beides schnell und effizient durchzuführen.

Der Erfolg von DPS hängt hauptsächlich von den technischen und finanziellen Faktoren ab. Daher sollte die Entwicklung dieser in Gebieten in Betracht gezogen werden, wo bereits mehrere isolierte Kraftwerke existieren, die nahe genug beieinander stehen, um effektiv zusammengeschlossen werden zu können. Basierend auf der hypothetischen Fallstudie der ländlichen Elektrifizierung von Junbesi(JURE, *Junbesi rural electrification*) kann man zu dem Schluss gelangen, dass ein Cluster von klein dimensionierten Wasserkraftwerken auf DPS-Basis, der eine Fläche von 100-115 km^2 abdeckt, auf einem Spannungsniveau von 3kV optimal ist und in anderen abgelegenen Regionen Anwendung finden könnte, die ähnliche Randbedingungen aufweisen. Solche Cluster von DPS können leicht mit dem regionalen Stromnetz verbunden werden.

Die Anwendung des entwickelten Konzepts und des Werkzeugs zur schnellen Analyse von ländlichen Elektrifizierungsalternativen wurde demonstriert(siehe Kapitel 7). Die Ergebnisse der Fallstudie werden in den Anhängen I-III dargestellt.

10.2 Ausblicke auf weitere Forschungsmöglichkeiten

Im Laufe der vorliegenden Arbeit wurde das ehrgeizige Ziel verfolgt, das Planungswerkzeug für HBDPS-Systeme so breit anwendbar und flexibel wie möglich zu machen und alle Planungs- und Entwurfskonzepte und auf bisherigen Kenntnissen basierende Mechanismen einschließen, die von Ingenieuren und Entscheidungsträgern zur Systemanalyse benötigt werden. Daher ist es nicht verwunderlich, dass sich diese Arbeit auf viele einschlägige Konzepte und Formulierungen, die von Ingenieur- und Wirtschaftsvereinigungen zur Projektentwicklung erprobt und anerkannt worden sind, bezieht. Aber in Hinblick auf die Zeit- und Arbeitsanforderungen, die ein so ehrgeiziges Projekt benötigt, kann man zu dem Schluss gelangen, dass nur ein Grundstein, auf welchem weitere Verbesserungen aufbauen können, gelegt wurde. Eines der wesentlichen Konzepte des entwickelten Modells ist die Verteilungsstrategie, auf Grund welcher es möglich war, Leistungs- und Energieausgleichsrechnungen unter Verwendung eines Computers durchzuführen(siehe Kapitel 6). Der Autor hofft, dass diese Strategie in der Zukunft zur Entwicklung eines elektronischen Standard-Stromregelsystems für den reibungslosen Betrieb eines dezentralen Stromerzeugungssystems in einer Echtzeitumgebung führen könnte. Die Untersuchung von k-Werten in den Kostenfunktionen für die Systemkomponenten müssten noch für andere Länder ausgearbeitet werden. Ähnlich wäre es auch möglich, einen Algorithmus für die Modellierung der einzelnen Komponenten eines Stromerzeugungssystems [Lubosny, (2003)] (z. B. Turbinen, Generatoren, Stromregler usw.) zu entwickeln, worin die zukünftige Arbeit an der vollständigen Entwicklung des derzeitigen Werkzeuges bestünde.

Wie schon vorher in Kapitel 2 erörtert, baut dieses Modell auf der computergestützten Umgebung von Microsoft® Excel 2000 auf. Excel bietet eine sehr vielschichtige und starke Programmierumgebung, indem es Visual Basic benutzt, mit dessen Hilfe das derzeitige Planungswerkzeug benutzerfreundlicher gestaltet werden kann. Es sollte hier auch überdies beachtet werden, dass der Simulations- und Optimierungsprozess eines Wasserkraftwerksystems und auch der ländlichen Elektrifizierung leistungsfähiger wird, wenn man ihn mit topographischen Karten verbindet. Weiterhin ist der Verbundbetrieb von DPS über das ganze Land ein zeitaufwendiges Unterfangen. Er ist in hohem Maße von der räumlichen Verteilung der Potentialgebiete in Bezug auf Stromversorgung und –nachfrage abhängig. Deshalb ist es notwendig, in das entwickelte Modell eine weitverbreitete Software wie beispielsweise GIS(*geographic information system*) zu integrieren. Mit der rasanten Entwicklung von Informationstechnologien und von GPS(*geographic positioning system*) sieht der Autor in naher Zukunft auch die Integration dieser Technologien in das derzeitige Simulations- und Optimierungsmodell. Ähnlich könnte auch das Matlab-basierte Simulink®-Programm für die zügige Prototypen-Entwicklung von dezentralen Stromerzeugungssystemen verwendet werden. Die Erfahrung zeigt bereits den Trend zur Nutzung solcher Werkzeuge unter zukünftigen Ingenieuren.

Daher gelangt der Autor zu dem Schluss, dass eine Verbindung des derzeitigen Modells, das zur Simulation und Optimierung von auf Kleinwasserkraftwerken basierten dezentralen Stromerzeugungssystemen entwickelt wurde, mit der kommerziell erhältlichen Software die zukünftige Aufgabe darstellt, um die ländliche Elektrifizierung zügig voranzutreiben.

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APPENDICES

A-I. Mathematical Formulation of Load Demand

The load demanded (P_{ij}) by j[th] consumer at i[th] time instant (in second) can be presented as:

$$P_{ij} = u_{ij} \cdot v_j \quad (A.1)$$

Where,

u_{ij}	Intensity of load demand $(0 \le u_{ij} \le 1)$,	$[-]$
v	Installed equipment load	$[kW]$

$$\text{The matrix } u_{ij} = \begin{pmatrix} u_{11} \cdots u_{1n} \\ \vdots \;\cdots\; \vdots \\ u_{m1} \cdots u_{mn} \end{pmatrix} \quad (A.2)$$

Where,

n	Number of consumers	$[-]$
m	Number of measuring points	$[-]$
i	i^{th} measuring point (time)	$[s]$
j	j^{th} consumer	$[-]$

In the matrix A.2 every column of vectors represents the measured value of a day for a consumer and every row of vectors represents the measured value of a time instant for all consumers. The installed load of each of the consumers is presented by the vector v

$$v_j = \begin{pmatrix} v_1 \\ \vdots \\ v_n \end{pmatrix} \quad (A.3)$$

The vector P_{ij} gives then the daily load curve of the network. If a large number of data points measured every day then the total energy demanded at the end of a year is determined as

$$W = \sum_{k=1}^{365} \frac{1}{\alpha} \sum_{i=1}^{m} P_{ij}^{k} \quad (A.4)$$

Where,

W	Annual energy demand	$[kWh]$
k	Number of days	$[-]$
α	Dimension factor = 3600 seconds in an hour	$[s \cdot hr^{-1}]$

The maximum load of the network is theoretically possible when the consumers use their entire connected load at the same time. This is determined as

$$V = \sum_{j=1}^{n} v_j \qquad (A.5)$$

Where,

V	Maximum load demanded by the equipment	[kW]
j	Number of consumer	[–]

A-II. Coincidence Factor for an Unlimited Number of Consumers

For a system that consists of n similar types of consumers, the coincidence factor may be estimated using the formula following [Hildebrand, 1993]:

$$g = g_\infty + \frac{1 - g_\infty}{\sqrt{n}} < 1 \qquad (A.6)$$

Where,

g_∞	Coincidence factor for an unlimited large number of households (see Table A.1)	[–]
n	Number of similar type of consumers	[–]

Table A.1 gives the values for the g_∞ in relation to the electrification stages and power demand. Using these values in the equation .A.6 a g = f (n) plot is presented in Figure A.1.

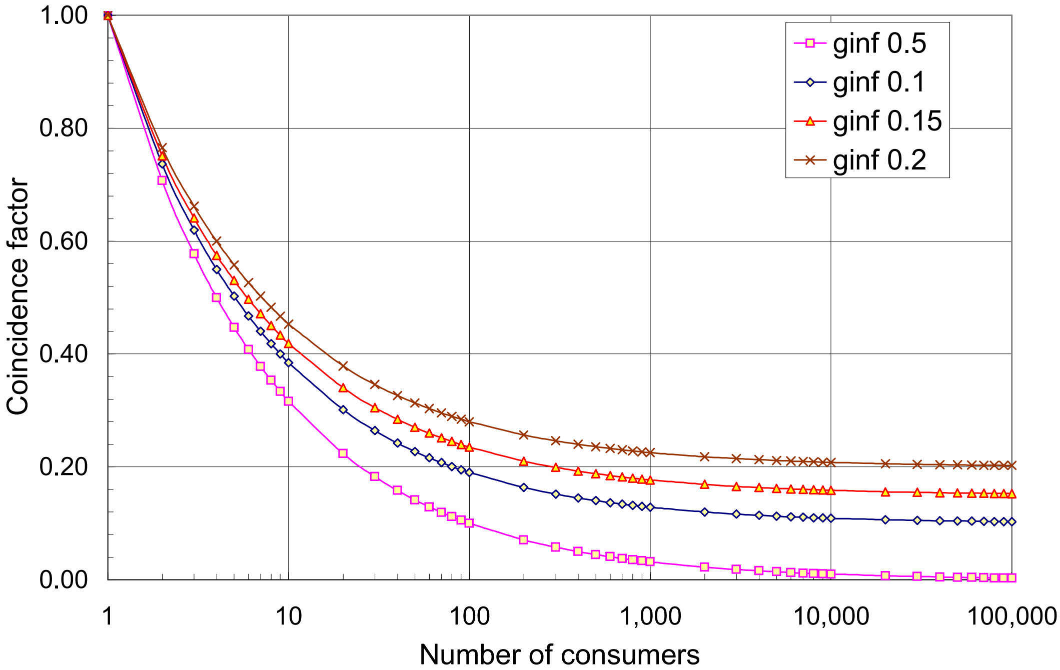

Figure A.1: Dependence of coincidence factor on the number of consumers

Table A.1: Coincidence factor household in relation to electrification stage [Stolz-Kesten, 1978]

Electrification stage	Power per household (W)	g_∞
Full electrification	20,000	0.05
Partial electrification	3,000	0.10
Weak electrification	1,500	0.15
New electrification	660	0.2

A-III. Cumulative Energy Conversion Curve

Ludin (1932) proposed a conversion curve W = f (P) as shown in Figure A.2. This curve is obtained by horizontally dividing the load curve into several intervals ΔP (Power differential) and increments of energy, $\Delta W = \Delta P t_i$, are computed for each of them. The cumulated energy for each load strip is plotted on the abscissa against loads on ordinate.

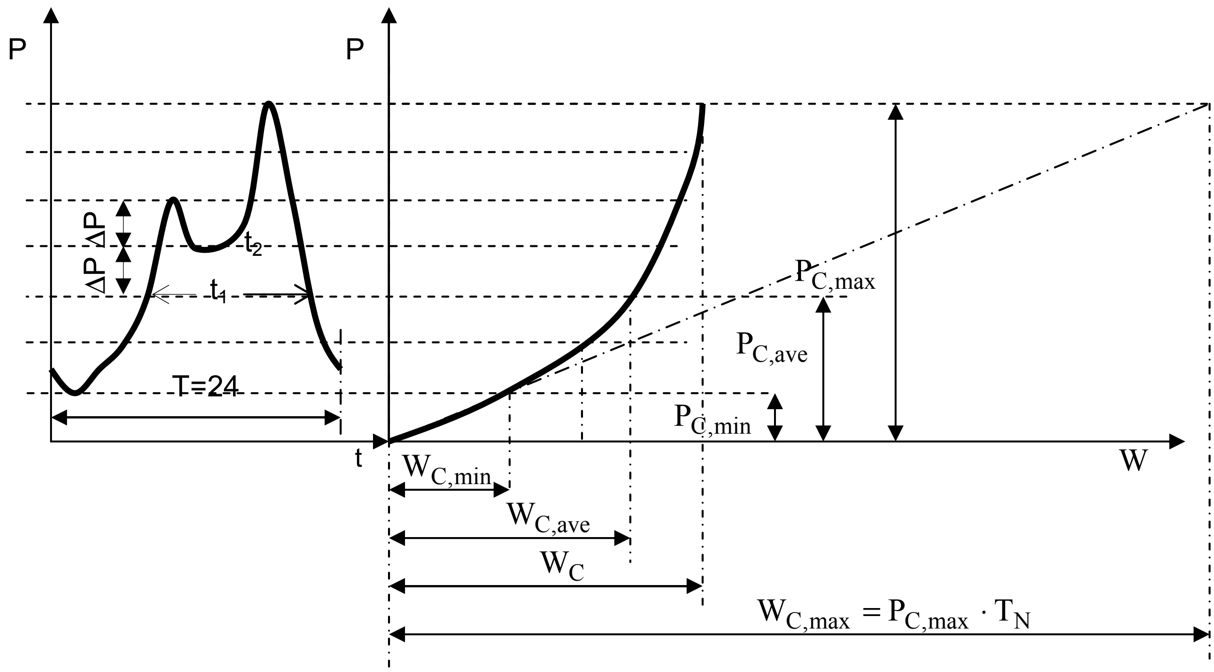

Figure A.2: Construction of a conversion curve for the analysis of a daily load curve

The conversion curve is characteristically a straight line at the base-load and a concave curve at the upper part of the base-load.

This curve is also referred to as the integral energy curve, meaning that the sum of the increments ΔPt_i gives the approximate value of the integral of the load curve P = f (t). The total energy under this curve is mathematically expressed as

$$W = \int_{PC,max}^{p} TdP \qquad (A.7)$$

Where,

dP	Load differential	[kW]
T	Period (24 hr for a day, 8760 hr for a year)	[hr]

The conversion curve is also useful in finding the period T as it is the derivative of the function W = f (P). In fact from Equation (A.7) it follows that

$$T = \frac{dW}{dP} \qquad (A.8)$$

A-IV. Equation for Theoretical Load Duration Curve

Let's assume the following exponential function for a load duration curve as shown in Figure A.3

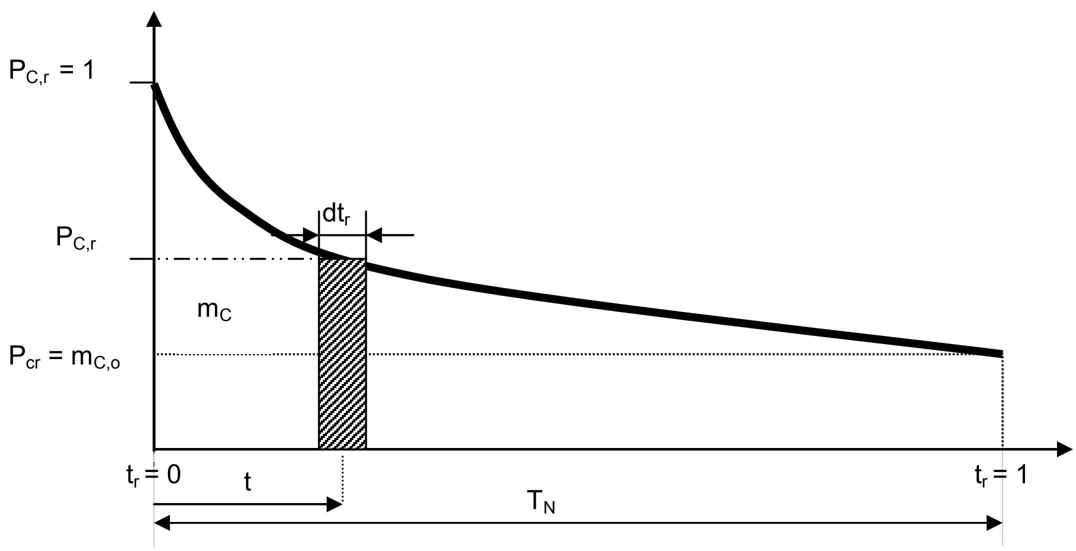

Figure A.3: Normalized load duration curve

$$P_{C,r} = 1 + \alpha t_r^{\beta} \qquad (A.9)$$

Where,

$P_{C,r} = \dfrac{P(t)}{P_{C,max}}$	Normalized load	[–]
$t_r = \dfrac{t}{T_N}$	Normalized period	[–]

The factor α and the exponent β can be found from the boundary conditions as follows:

If t = 0, then t_r = 0 and $P_{C,r} = 1$

If t = T_N, then t_r = 1 and $P_{C,r} = m_{C,o}$

Therefore, the factor $\alpha = m_{C,o} - 1$

The exponent is found from the load utilization factor)

$$m_C = \frac{W_C}{W_{C,max}} = \int_{t=0}^{T_N} \frac{P(t)}{P_{C,max}} d\left(\frac{t}{T_N}\right) = \int_{t_r=0}^{1} P_{c,r} dt_r = \int_{t_r=0}^{1} (1 + \alpha t_r^{\beta}) dt_r \qquad (A.10)$$

It may be noted that a load utilization factor is geometrically the area under the normalized load-duration curve

$$m_C = 1 + \frac{\alpha}{\beta + 1} = 1 + \frac{m_{C,o} - 1}{\beta + 1} \qquad (A.11)$$

From where,

$$\beta = \frac{m_C - m_{C,o}}{1 - m_C} \qquad (A.12)$$

Finally, the normalized load-duration equation takes the following form:

$$P_{C,r} = 1 + (m_{C,o} - 1) t_r^{\frac{m_C - m_{C,o}}{1 - m_C}} \qquad (A.13)$$

Or the required power duration curve in absolute terms can be found as:

$$P_C(t) = P_{C,max} \left[1 + \left(\frac{P_{C,min} - P_{C,max}}{P_{C,max}} \right) \left(\frac{t}{T_N} \right)^{\frac{P_{C,ave} - P_{C,min}}{P_{C,max} - P_{C,ave}}} \right] \qquad (A.14)$$

Mosonyi (1948) proposed a theoretical duration-curve to derive a formula for the characteristic mass-curve V = f(t) which is widely used in the design of reservoirs. For this he considered an equation of parabolic decreasing curve with time and discharge as two variables. The constant was defined by the boundary conditions at t = 0 and t = T_N, and the exponent was defined as a fixed value of 6. This led to the introduction of a dimensionless coefficient φ as characteristics for the relative extremity of run-off, which itself is dependable mainly on the size and geology of the drainage area.

$$Q(t) = Q_{ave} \cdot \left[1 - \varphi + 7 \cdot \varphi \cdot \left(\frac{T_N - t}{T_N} \right)^6 \right] \quad \text{(A.15)}$$

Where,

$Q(t)$	Flow at duration t	$[m^3 \cdot s^{-1}]$
Q_{avr}	Average flow	$[m^3 \cdot s^{-1}]$
$\varphi = \frac{m'-1}{m'+6}$	Dimensionless coefficient	$[-]$
$m' = \frac{Q_{max}}{Q_{min}}$	Ratio of flow extremity	$[-]$

The difficulty in using the Equation A.15 for the present work lies in the determination of the dimensionless coefficient. It needs an analysis of a lot of drainage areas and the use of logarithmic relationships and tabular data to obtain its accurate values [Mosonyi 1948]. Such data are not readily available for the planning of small hydropower projects. As a way out the author proposes, in analogy to the Equation A.14 the following Equation:

$$Q(t) = Q_{max} \cdot \left[1 + \left(\frac{Q_{min} - Q_{max}}{Q_{max}} \right) \cdot \left(\frac{t}{T_N} \right)^{\frac{Q_{ave} - Q_{min}}{Q_{max} - Q_{ave}}} \right] \quad \text{(A.16)}$$

Where,

$Q(t)$	Flow at duration t	$[m^3 \cdot s^{-1}]$
Q_{max}	Maximum flow	$[m^3 \cdot s^{-1}]$
Q_{min}	Minimum flow	$[m^3 \cdot s^{-1}]$
Q_{ave}	Average flow	$[m^3 \cdot s^{-1}]$

As will be noticed, Equation A.16 allows a quick estimation of discharge. Hence this tool has been used in this work for power system optimisation and the sensitivity analysis.

Figure A.4 presents a comparison between the monthly average flow duration curve of Heldung River in Nepal [Thike, 1998] and the derived flow duration curve using Equation A.16. The calculated average to maximum flow ratio is only 0.36 % higher than the actual, which is acceptable for the preliminary calculation.

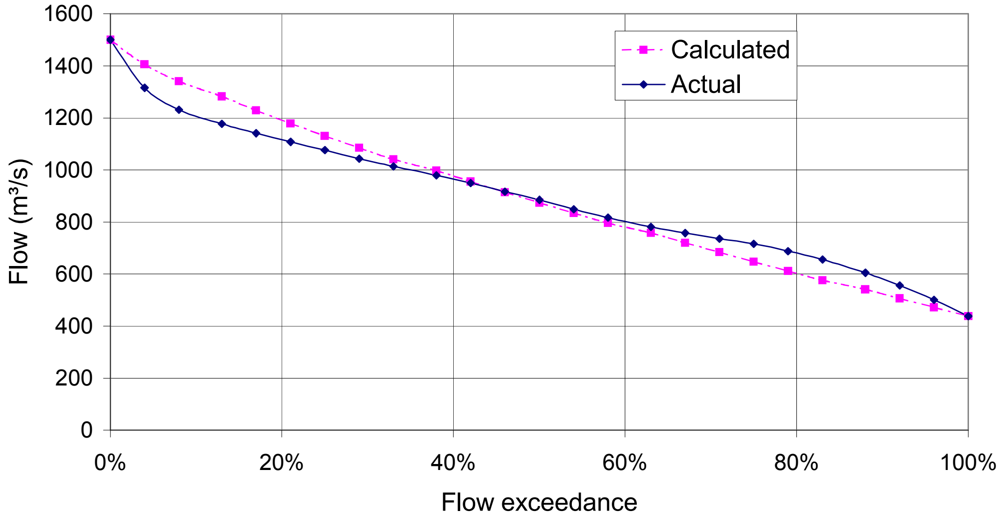

Figure A.4: Average monthly discharge curve of Heldung River in Nepal

A-V. Definition of Ecological Efficiency

- The energy payback period τ_E is defined as the ratio of the cumulated energy needed for the manufacturing, implementation of the plant to the annual net-energy production [Kugeler und Philippen, 1990].

$$\tau_E = \frac{\sum_i W_i}{\int_0^T P(t)dt} = \frac{\sum_i W_i}{P_{ave,Sys} \cdot T} \tag{3.22}$$

Where,

$\tau_E \cdot T$	Energy amortization period	$[a]$
$\sum_i W_i$	Cumulated energy used-up for manufacturing, implementation of the plant	$[kWh]$
$P_{ave,Sys}$	Annual average power production of the plant	$[kW]$
T	Hours in a year (8760 hrs)	$[hrs]$

For small hydropower plants τ_E is 2 to 3 years (see Table 3.1).

- The energy-harvesting factor expresses the ratio of generated energy during the N-years of plant's lifetime to the sum of energy needed for implementation, operation and demolition of the plant [Kugeler und Philippen, 1990].

$$f_E = \frac{\sum_1^N W_{life}}{\sum_i W_i + \sum_1^N W_{O,M,D}} = \frac{N\int_0^T P(t)dt}{\sum_i E_i + n\varepsilon} = \frac{N \cdot P_{ave} \cdot T}{\tau_E \cdot P_{ave} \cdot T + N\varepsilon} \quad (3.23$$

Where,

f_E	Energy-harvesting factor	$[-]$
$\sum_1^N W_{life}$	Cumulated net-energy supply during the planned life period of the plant	$[kWh]$
$\sum_i W_i$	Cumulated energy used-up for manufacturing and implementation of the plant	$[kWh]$
$\sum_1^N W_{O,M,D}$	Total energy needed for operation, maintenance and demolition of the plant	$[kWh]$
N	Life period of a plant	$[a]$
ε	Characterizes the energy needed to operate, maintain and demolish the plant during its life period	$[a]$

f_E for small hydropower plants ranges from 40 to 100 (see Table 3.1).

A-VI. Definition of Economic Efficiency

The **present value method** is based on the concept that allows present judgment of the costs and the benefits that will be incurred in the future. Thus the time horizon is an important part in this method. The process of bringing the future values back to present is known as **discounting**. This is done by multiplying the future sum by a present value factor (PVF). In this regard a real discount rate in percentage (real interest rate) that expresses the time value of money (inflation free) has to be considered. The present value factor is thus defined as:

$$PVF = \frac{1}{(1 + r^*)^t} \quad (A.17)$$

The inflation free interest rate or the real discount rate (r*) is defined for one year as:

$$r^* = \frac{1+r}{1+i} - 1 \quad (A.18)$$

Where,

r	Market interest rate	$[\%]$
i	Inflation rate	$[\%]$

The **Net Present Value** of the project (NPV) shows the present value of the sum of future net value in constant dollars discounted back to present time using a real discount rate. The net value is determined by deducting the annual project costs from the annual benefit over project economic life. NPV is mathematically expressed as:

$$NPV = -\sum_{k=1}^{n} I_K \cdot (1 + r^*)^K + \sum_{t=0}^{T} \frac{B_t - C_t}{(1 + r^*)^t} + \frac{R}{(1 + r^*)^T} \tag{A.19}$$

Where,

B_t	Project benefit at t^{th} year in constant dollars	[\$]
C_t	Project cost at t^{th} year in constant dollars	[\$]
r^*	Real discount rate (definition is given below)	[%]
I_K	Partial investment in K^{th}-year	[\$]
n	Investment period (beginning of payment series)	[a]
R	Rest value of a plant at the end of its life	[\$]
t	Index representing the year under consideration	[a]
T	Project's economic life	[a]

The NPV is one of the decisions making tool and widely used for comparing two or more project options in hand. It may also serve to define the optimal size of a project.

Figure A.5 shows an example for selecting optimum design discharge for a hydropower plant using NPV method.

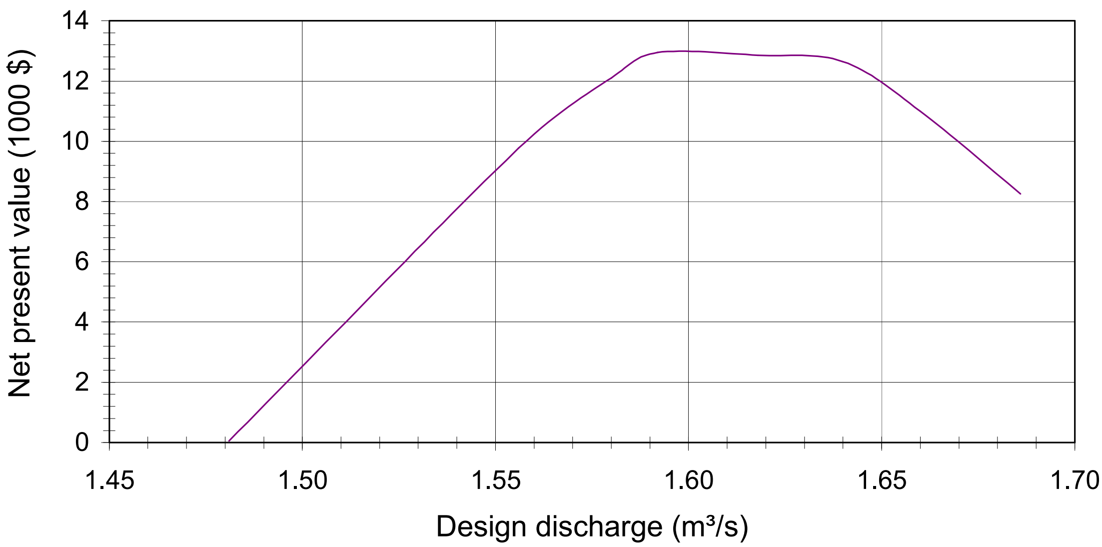

Figure A.5: NPV used for selecting design discharge for a hydropower plant

It is obvious that increasing design discharge and hence the project size after a certain quantity is not advisable as the NPV though positive falls back from its maximum value.

Thus the criteria for the economic judgment of a project using NPV method are two folds:

1. NPV should be positive
2. NPV should be highest among all other alternatives.

The first criterion ensures that a project is worth undertaking relative to the base case by contributing more incremental benefits than the costs that a project absorbs. The second criterion ensures that maximum benefits are obtained in case of unrestricted access to capital fund [Ayyub, 2003].

An annuity method is based on the concept that a discounted uniform annual amount expended or paid that is equal to a present investment amount to cover some given activities over a fixed period of time.

Most widely used factors in this method are the **sinking fund factor** and the **capital recovery factor**. The sinking fund factor is functionally noted as (A/F,r*,t) and mathematically written as

$$(A/F, r^*, t) = \frac{r^*}{(1+r^*)^t - 1} \tag{A.20}$$

Where,

A	Equal annual payment at the end of each period for n periods	[$]
F	Amount at the end of n periods	[$]

The **sinking fund** is a separate amount into which payments (usually annual) are made to grow some desired amount in the future.

The **capital recovery** factor concerns to make uniform payments that are discounted at the rate r from the present value. It is functionally noted as (A/P,r,n) and mathematically expressed as:

$$(A/P, r^*, t) = \frac{r^*(1+r^*)^t}{(1+r^*)^t - 1} \tag{A.21}$$

Where,

A	Equal annual payment at the end of each period for n periods	[$]
F	Amount at the end of n periods	[$]

Most common form of economic efficiency of a system is the **benefit-cost ratio**. The benefit-cost ratio method may also be done in the present value configuration.

$$\text{Economic efficiency} = \frac{B}{C} = \frac{\sum_{t=1}^{T} \frac{B_t}{(1+r^*)^t}}{\sum_{t=1}^{T} \frac{C_t}{(1+r^*)^t}} \tag{A.22}$$

Unlike the physical (technical) efficiency, the economic efficiency has to be more than unity. A project cannot be said to be economically effective and discarded if the ratio is less than 1. This method should be used with caution because of chance to mislead the decision-making [Mosonyi and Buck, 1972].

Least cost planning approach (LCP): This approach is applied when the benefits from different alternatives are estimated to be the same. Hence, either only the least-total costs of different alternatives over the life of a project are compared or the least-total-annual costs are compared. In the first approach the timing of costs as required by the discounting method is ignored, whereas in the second approach an interest cost is added to the total cost. The later approach leads to confusion between economic and financial analysis [James and Lee, 1971].

Internal rate-of-return (ROR) method determines the discount rate due to which the equivalent benefit cash flow equals the equivalent cost cash flow at the end of project's economic life. In other words, it is the discount rate that turns the NPV to zero.

This represents the rate of return on an investment. It is obtained only through iteration. Figure A.6 presents an example of determination of rate of return with sensitivity analysis using base, pessimistic and optimistic cases.

It may be seen that NPV is zero at 10 %, 14.5 % and 20 % discount rates for pessimistic, base and optimistic cases respectively. Hence, these discount rates are the internal rate of returns. These values are compared with a minimum attractive rate of return (MARR) of a country.

If a government sets the MARR at 10 % as in the case of the Government of Nepal [Norconsult, 1998], the project in example is attractive at base case and questionable at pessimistic case. The optimistic case shows that the project may earn more than 20 % of ROR.

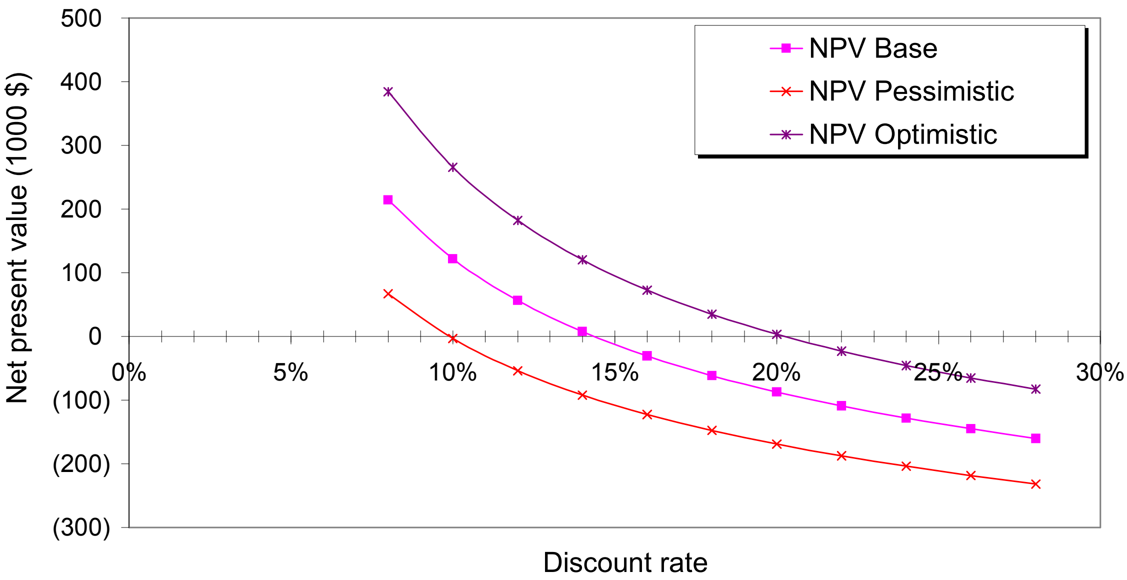

Figure A.6: Determination of internal rate of return for three sensitivity test cases

Public utilities some times use **profitability index** or rate of return on investment, which is the ratio of NPV to initial investment.

$$\text{profitability index} = \frac{\text{NPV}}{\text{Initial investment}} \tag{A.23}$$

Simple payback period is the time over which the accumulated net benefits from a project equal the initial investment minus any subsidy in this project [ITDG/Nepal, 1997]. The net benefits are arrived after all initial outlays, including interest and sinking fund contribution, operation and maintenance, management and customer service costs have been deducted from a project revenue. Hence it is determined as

$$\text{Simple payback} = \frac{\text{Initial investment} - \text{Subsidy}}{\text{IAnnual revenue} - \text{Annual O\$M}} \tag{A.24}$$

The simple payback period is often used as an index of economic merit for investment in the private sector and only occasionally for public utility projects. It is simple to understand but has a demerit that once the initial outlays have been arrived it does not take into account the further life of the asset and the revenue the asset can earn. From an economic point of view, this method disregards the time value of money (i.e., interest on capital).

A-VII. Cost-function of Various Components of a Hydropower Project

In Table A.2 a collection of cost-functions of various components of a hydropower project is given.

Table A.2: Cost-functions of various components of a hydropower project

Component	Formula	Remarks
Planning	$C_{Plan} = k \cdot 10^3 \cdot \left(\frac{P}{h_f^{0.3}}\right)^{0,74}$	• in DM • K value depends on the type of planning studies (refer Gordon, 1988 for details) • K for small hydro < 10 MW ranges from 2.8 to 1,528
Civil works	$C_{Civil} = 43{,}000 \cdot \left(\frac{P}{h_f^{0.3}}\right)^{0,71}$	• (Valid for P< 2MW, h_f< 15 m), Price basis 1995 in DM. • 5% to be added for site clearance. • Giesecke et al (1993)
Mechanical Equipment	$C_{Mechl} = 31{,}555 \cdot \left(\frac{P}{z \cdot h_f^{0.3}}\right)^{0,65} \cdot (z + 0.1)$	• (Valid for P< 2MW, h_f< 15 m), Price basis 1995 in DM • Turbine, regulators, gears, coldwater supply, drainage, ventilation etc. • Giesecke et al (1993)
Electrical equipment	$C_{Elec} = 1{,}300 \cdot \left(\frac{P}{h_f^{0.3}}\right)^{0,98}$	• (Valid for P< 2MW, hf< 15 m), Price basis 1995 in DM • Generator, Transformer, main switchgears and controllers. • Giesecke et al (1993)
Steel	$C_{steel} = 2{,}600 \cdot \left(\frac{P}{h_f^{0.3}}\right)^{0,84}$	• (Valid for P< 2MW, hf< 15 m), Price basis 1995 in DM • Racks and Gates • Giesecke et al (1993)
Operation & Maintenance	$C_{O\&M} = 1{,}600 \cdot P^{0.55}$	• (Valid for P< 2MW, h_f< 15 m), Price basis 1995 in DM • Giesecke et al (1993)
Miscellaneous	Consulting: 5-17 % for small plants 6-8 % for large plants Others: 3-4 % of the civil works	• Giesecke et al (1993)
Total investment	$C_P = k \cdot 10^3 \cdot \left(\frac{1}{P^{0.3} \cdot h_f^{0.15}}\right)$	• In US \$ • K = 3.5…4.5 • Harvey 1993
	$C_P = k \cdot 10^3 \cdot \left(\frac{1}{P^{0.15}}\right)$	• in DM/kW • K= 9.4 • Dubach in Babanek 1982
Mechanical and equipment	$C_{Mech} = k \cdot 10^3 \cdot \left(\frac{P}{h_f^{0.287}}\right)^{0,82}$	• in US \$ • Recommended for P= 50 kW to 40 MW, h = 4 m to 1000 m. • Gulliver and Dotan 1984 and Gulliver and Roger 1991.
z	Number of mechanical units	

A-VIII. Formula for Determination of Turbine Efficiency

Table A.3 provides some formulas for turbine efficiency that have been derived from RETScreen®. RETScreen® is free software consisting of 9 different models for planning and design of various renewable energy technologies including small hydropower.

Table A.3: Formula for determination of approximate turbine efficiency [modified after RETScreen, 2004]

Type Of turbine	Formula for calculating turbine efficiency	
Cross-flow	$0.79-0.15\cdot\left(\frac{Q_d-Q_i}{Q_d}\right)-1.37\cdot\left(\frac{Q_d-Q_i}{Q_d}\right)^{14}$	(A.25)
Pelton	$\left[1-\left\{(1.31+0.025\cdot J)\cdot\left\|\left(\frac{(0.662+0.001\cdot J)\cdot Q_d-Q_i}{(0.662+0.001\cdot J)\cdot Q_d}\right)\right\|^{(5.6+0.4\cdot J)}\right\}\right]\cdot$ $\cdot 0.864\cdot d^{0.04}$	(A.26)
Francis	$\left\{1-\left[1.25\left\|\left(\frac{\left(0.65\cdot Q_d\cdot n_q^{0.05}-Q_i\right)}{0.65\cdot Q_d\cdot n_q^{0.05}}\right)\right\|^{\left(3.94-0.0195\cdot n_q\right)}\right]\right\}\cdot$ $\left(0.919-\left\{\frac{n_q-56}{256}\right\}^2+0.081+\left\{\frac{n_q-56}{256}\right\}^2\cdot\left(1-0.789\cdot d^{-0.2}\right)\right)-$ $0.0305+0.005\cdot R_m$	(A.27)
Kaplan	$\left\{1-\left[3.25\left\|\left(\frac{(0.75\cdot Q_d-Q_i)}{0.75\cdot Q_d}\right)\right\|^{6}\right]\right\}\cdot$ $\left(0.905+\left\{\frac{n_q-170}{700}\right\}^2+0.095+\left\{\frac{n_q-170}{700}\right\}^2\cdot\left(1-0.789\cdot d^{-0.2}\right)\right)-$ $0.0305+0.005\cdot R_m$	(A.27)
Where	J Number of jets in case of impulse turbines R_m Turbine manufacture/design coefficient (2.8 to 6.1) i i^{th} time interval	

A-IX. Wind Velocity Distribution Function

The scale and shape factors were determined by correlating the estimated data with measured data using the following relationship:

$$f_{Weibul}\left(v_{ava}\right)=\frac{k}{C}\cdot\left(\frac{v_{ave}}{C}\right)^{k-1}\cdot\exp\left(-\left(\frac{v_{ave}}{C}\right)^{k}\right) \qquad (A.29)$$

Where,

$f_{Weibul}\left(v_{ave}\right)$	Weibull frequency distribution of wind speed	[–]
v_{ave}	Wind speed	$[kg \cdot m^{-3}]$
k	Shape or form factor	[–]
C	Scale factor	[–]

A-X. Air Density Correction

For an altitude up to 6000 m, the following formula may be used to determine the air density [Patel, 1999].

$$\rho=\rho_0-1.194\cdot 10^{-4}\cdot H_m \qquad (A.30)$$

Where,

ρ	Air density at wind plant site	$[kg \cdot m^{-3}]$
ρ_O	Air density at sea level	$[kg \cdot m^{-3}]$
H_m	Wind plant site elevation	[m]

A-XI. Mounting Height Correction

The developed algorithm automatically corrects the wind speed using the following formula

$$v_{HH}=v_{ref}\cdot\frac{\ln\left(\frac{H_{HH}}{z}\right)}{\ln\left(\frac{H_{ref}}{z}\right)} \qquad (A.31)$$

Where,

v_{HH}	Wind velocity at hub height	$[m \cdot s^{-1}]$
v_{ref}	Wind velocity at reference height	$[m \cdot s^{-1}]$
H_{HH}	Turbine hub height	[m]
H_{ref}	Reference height	[m]
z	Surface roughness length	[m]

A-XII. Geographical Position of a Site with respect to Sun

Figure A.7 schematically depicts all three important angles required to define the geographical position of a photovoltaic plant site (P) with respect to sun light

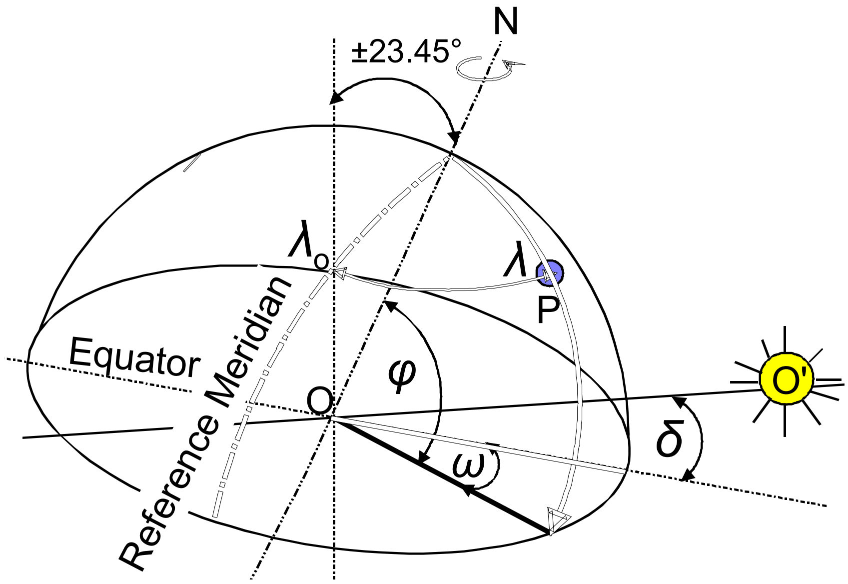

Figure A.7: Determination of position of a site P with respect to sunlight (after Khartchenko, 1995)

The **declination angle** δ defines the angle of position of earth's axis relative to sun. It is the angle between the line passing through the centres of the sun and the earth and its projection on the surface of the Equator. Because the earth always keeps in the same angle of rotation about 66.55° against the orbital plane of the earth, the declination angle fluctuates between ± 23.45° on 22 December (Winter solstice) and + 23.45° on 22 June (Summer solstice). It is zero on 21 March (Vernal equinox) and 22 September (Autumnal equinox). For a specific day in a year, it may be calculated approximately using Cooper's formula as follows:

$$\delta = 23.45^\circ \cdot \sin\left(360^\circ \cdot \frac{284 + n}{365}\right) \qquad \text{(A.32)}$$

Where,

$n = 30.3 \cdot (\text{Month} - 1) + \text{day}$ Julian day of the year [day]

The **solar hour angle** ω defines the true place time (TPT) for the site meridian λ. It is the angular displacement of sun from solar noon on the plane of apparent travel of the sun. It can be calculated using the following expression:

$$\omega = (12h - t_{sol}) \cdot \frac{360^\circ}{24} \qquad \text{(A.33)}$$

Where,

t_{sol} True place time [hrs]

The **true place time**, also known as **solar time**, characterizes the position of the sun with respect to a place on the earth. It defers from the local standard time because of the deviation of the site meridian from the reference meridian. It must also be corrected to consider the non-circular form of the earth's orbit.

$$t_{sol} = t_{std} + \frac{\lambda_o - \lambda}{15^o} + Z \qquad \text{(A.34)}$$

Where,

t_{sol}	True place time	[hrs.]
t_{std}	Local standard time	[hrs.]
λ_o	Reference meridian	[degree]
λ	Site meridian	[degree]
Z	Time correction factor	[degree]

The time correction factor is then determined using the following equation [Manuwell et al, 1998].

$$Z = 3.82\left[\begin{array}{l} 0.00075 + 0.001868\cdot\cos\left(\frac{(n-1)\cdot 360^o}{365}\right) \\ -0.032077\cdot\sin\left(\frac{(n-1)\cdot 360^o}{365}\right) - 0.014615\cdot\cos\left(\frac{2\cdot(n-1)\cdot 360^o}{365}\right) \\ -0.04089\cdot\sin\left(\frac{2\cdot(n-1)\cdot 360^o}{365}\right) \end{array}\right] \qquad \text{(A.35)}$$

A-XIII. Determination of Global Irradiance

The global irradiance on the tilted solar panel is the sum of direct (**beam**), diffused (**scattered**) and any reflected (**Albedo)** irradiance from ground [Quaschning, 2003].

$$S_{G,Til} = S_{b,Til} + S_{d,Til} + S_{r,Til} \qquad \text{(A.36)}$$

Where,

$S_{G,Til}$	Global irradiance on tilted surface	$[W \cdot m^{-2}]$
$S_{b,Til}$	Beam irradiance on tilted surface	$[W \cdot m^{-2}]$
$S_{d,Til}$	Diffused irradiance on tilted surface	$[W \cdot m^{-2}]$
$S_{r,Til}$	Albedo irradiance on tilted surface	$[W \cdot m^{-2}]$

The solar radiation inside the atmosphere depends on the factor known as **clearness index**, which is the ratio between the actual average irradiance on the horizontal plane to the average irradiance outside the earth's atmosphere. This index is used to determine the direct and diffused irradiance using an empirical relationship.

Finally, the irradiance on the tilted plane of the array for each time step of simulation is determined given the average irradiance on horizontal surface at each time step of simulation. This is done using the equation based on the concept of an anisotropy sky [Duffie and Beckman, 1991]:

$$\bar{S}_{G,Til} = \left(\bar{S}_b + \bar{S}_d \cdot A_i\right) \cdot R_b + \bar{S}_b \cdot (1 - A_i) \cdot \left(\frac{1+\cos(\gamma_{PV})}{2}\right) \cdot \left[1 + f \cdot \sin^3\left(\frac{\gamma_{PV}}{2}\right)\right] + \bar{S} \cdot \rho_g \cdot \left(\frac{1-\cos(\gamma_{PV})}{2}\right) \quad (A.37)$$

Where,

$\bar{S}_{G,Til}$	Global irradiance on tilted surface	$[W \cdot m^{-2}]$
$\bar{S}_b$	Beam component of average irradiance on horizontal surface	$[W \cdot m^{-2}]$
$\bar{S}_d$	Diffused component of average irradiance on horizontal surface	$[W \cdot m^{-2}]$
$\bar{S}$	Average irradiance on horizontal surface	$[W \cdot m^{-2}]$
A_i	Anisotropy index	[–]
R_b	Ratio of beam radiation on tilted surface to the horizontal	[–]
f	Modulating factor	[–]
ρ_g	Ground reflectance	[–]
γ_{PV}	Slope angle of tilted surface with respect to horizontal	$[W \cdot m^{-2}]$

Since the radiance is strongly different particularly with clear sky depending upon direction, an anisotropy approach is usually selected for the computation of the global radiation on the inclined surface.

The **anisotropy index**, which indicates the transmittance of the atmosphere for beam radiation, is calculated as:

$$A_i = \frac{\bar{S}_b}{\bar{S}_o} \quad (A38)$$

Where,

$\bar{S}_o$	Average irradiance outside the earth's atmosphere	$[W \cdot m^{-2}]$
$\bar{S}_b$	Beam component of average irradiance on horizontal surface	$[W \cdot m^{-2}]$

The average irradiance outside the earth's atmosphere is determined as

$$\bar{S}_o = \bar{S}_{SC}\left(1 + 0.33 \cdot \cos\left(\frac{360 \cdot n}{365}\right)\right) \cdot \cos(\theta_z) \quad (A.39)$$

Where,

$\bar{S}_{SC}$	Solar constant (1367)	$[W \cdot m^{-2}]$

The modulating factor f can then be calculated as:

$$f = \left(\frac{\bar{S}_b}{\bar{S}} \right)^{0.5} \quad \text{(A.40)}$$

The beam irradiance is obtained by subtracting the diffused irradiance from average global irradiance on horizontal surface as follows:

$$\bar{S}_b = \bar{S} - \bar{S}_d \quad \text{(A.41)}$$

To calculate the diffused component of average global irradiance via the correlation of Erbs et al (1982), first of all it is necessary to determine the clearness index that shows the radiation that reaches to earth surface after attenuation by the atmosphere and clouds, as

$$k_T = \frac{\bar{S}}{\bar{S}_o} \quad \text{(A.42)}$$

The diffused irradiance is the function of k_T and found from the following relations:

$$\bar{S}_d = \bar{S}(1.0 - 0.09 k_T) \quad \text{for} \quad k_T \le 0.22 \quad \text{(A.43)}$$

$$\bar{S}_d = \bar{S}\left(0.9511 - 0.1604 k_T + 4.388 k_T^2 - 16.638 k_T^3 + 12.336 k_T^4\right) \quad \text{for} \quad 0.22 < k_T \le 0.80 \quad \text{(A.44)}$$

$$\bar{S}_d = 0.165 \cdot \bar{S} \quad \text{for} \quad k_T > 0.80 \quad \text{(A.45)}$$

Finally R_b, which is the ratio of beam radiation on the tilted surface to that on a horizontal surface at any time or, in other words, it is the ratio of the angle of incidence to the zenith angle, is determined as:

$$R_b = \frac{\bar{S}_{b,T}}{\bar{S}_b} = \frac{\cos(\theta_{gen})}{\cos(\theta_z)} \quad \text{(A.46)}$$

Where,

θ_{gen}	Angle of incidence; angle between sun's rays and the line perpendicular to panel	[deg.]
θ_z	Zenith angle, angle between sun's rays and the line perpendicular to the earth's surface	[deg.]

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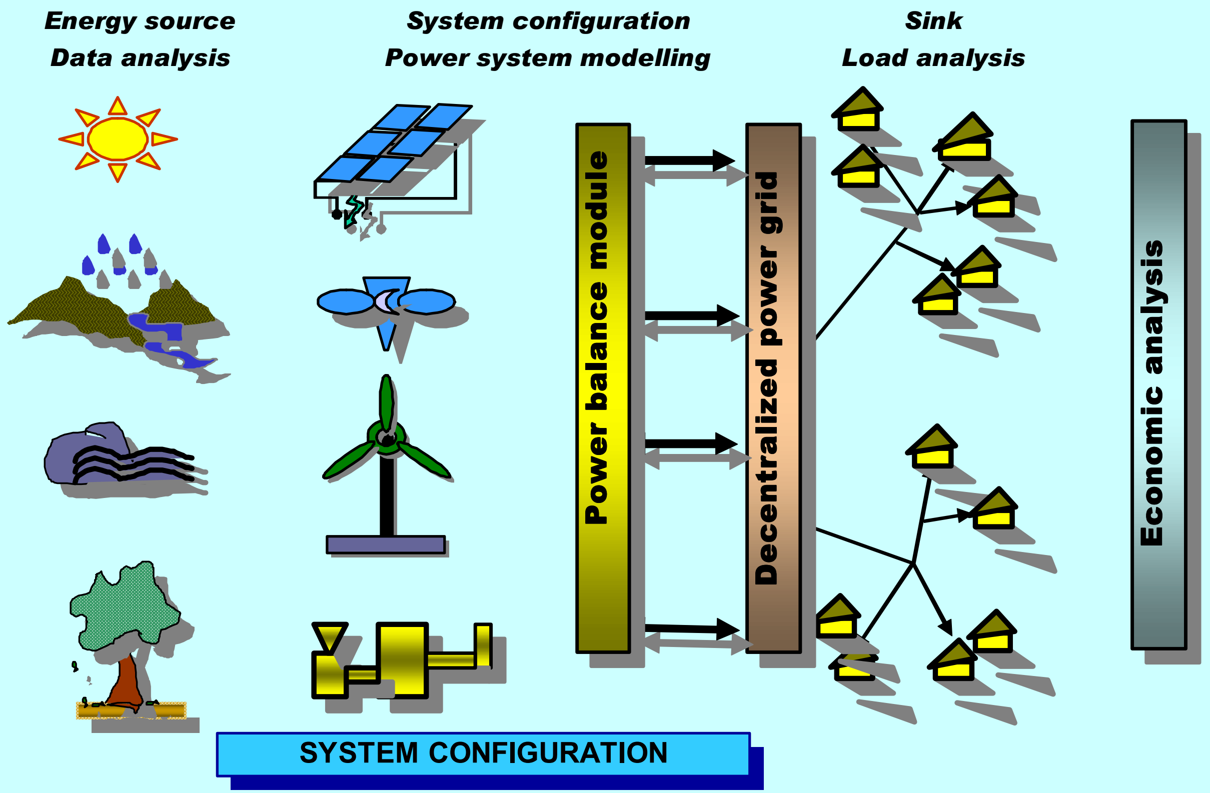
Decentralized Power System Simulation and Optimisation Model (DEPSO) Version 01



*This is the first version of the Decentralized Power System Simulation and Optimisation Model (**DEPSO**).*

This model is capable for designing, simulation and optimization of a decentralized power system for rural electrification consisting several renewable power plants and load centers.

Please start entering your data by clicking on the corresponding icons. Please be sure that you have entered all data in the cells with blue letters. Cells without color and black letters are write protected.

To start with, please click on system configuration. Help! tips and web hyperlinks are under construction.

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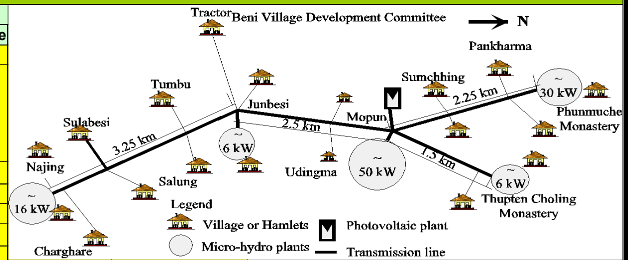
Decentralized Power System Simulation and Optimisation Model (DEPSO)

Project information:			Administrative location		Geographical location	
Project	Junbesi Rural Electrification (JURE)		VDC	Beni	Easting	86°30'
System Analyst	Er. Ramesh Maskey		District	Solu	Northing	27°30'
Date			Region	EDR	Altitude	2800 m
Organisation	IWK, University of Karlsruhe		Country	Nepal	No. HH	300

System setting		Najin			Junbesi			Mopun (I)			Thupten		Mopun (II)		Phunmoche	
Node		1	2	3	4	5	6	7	8	9	10	11	7	12	13	14
Regional grid		No														
Grid type		Isolated														
Type of energy production		Daily														
System load (Primary load I)	SL		1	1	1		1	1		1	1			1	1	
Grid configuration	TL		1	1	1	1	1	1	1	1	1	1	1	1	1	1
Nodes load factor	m		52%	53%	54%	52%	52%	52%	52%	52%	52%	52%	52%	52%	52%	
Power plants																
Hydropower plants	Hp	1				1			1			1	1			1
Hydropower project type		Run-off-river				Run-off-river			Run-off-river			Run-off-river	Run-off-river			Run-off-riv
Hydrology method		Flow duration curve				Flow duration curve			Flow duration curve			Flow duration	duration curve			Flow duration
Solar power plants	Sp								1							
Wind power plants	Wp								1							
Balance of system									0							
Battery (Primary load II)	Bs								1							
Secondary load (Battery: deferrable load I)	Ps								0							
Secondary load (Pump: deferrable load II)	DI								0							
Ballast load (deferrable load III)	BI								0							

Decision variables

System components			Najin	Junbesi	Mopun (I)	Mopun (II)	Thupten	Phunmoche
Percent time rated flow equalled or exceeded	T	[%]	95%	63%	100%	100%	81%	100%
Type of Hydro-turbine	Pelton =1; Cross-flow =2; Francis =3; Kaplan =4		1	1	2	2	2	2
Number of machines	z_M=1,2	[-]	1	1	1	1	1	1
Number of jets	J=1,2,3,4,6	[-]	5	1	1	1	1	1
Min. turbine setting height	hs	[m]	1,00	2,00	1,00	1,00	2,00	1,00
Penstock diameter	D_i	[m]	0,20	0,30	0,35	0,35	0,35	0,27
Penstock thickness	t	[m]	0,040	0,010	0,010	0,010	0,010	0,010
Canal free-board (factor of safety)	F	[-]	2,60	2,50	2,50	2,50	2,50	1,70
Flow contol through turbine	PF	[%]	100%	100%	100%	100%	100%	100%
Solar (PV) array size	A_{PV}	[m²]	0	0		70	0	0
Collector slope angle		[deg.]	0	0	0	30	0	0
Surface azimuth angle		[deg.]	0	0	0	45	0	0
Wind rotor diameter	D_{WT}	[m]	0	0	0	12	0	0
Turbine hub height	H	[m]	0	0	0	15	0	0
Size of battery bank (Primary load II)	BB	[kW]	0	0	0	16	0	0
Size of additional battery bank (Prim. Load II)	BB	[kW]	0	0	0	2	0	0
Size of diferrable load I	DL I	[kW]	0	0	0	10	0	0
Size of deferrable load II	DL II	[kW]	0	0	0	20	0	0
Transmission line capacity	TR	[kV]	0	0	0	3	0	0
Conductor size	A_c	[mm²]	0	0	0	50	0	0



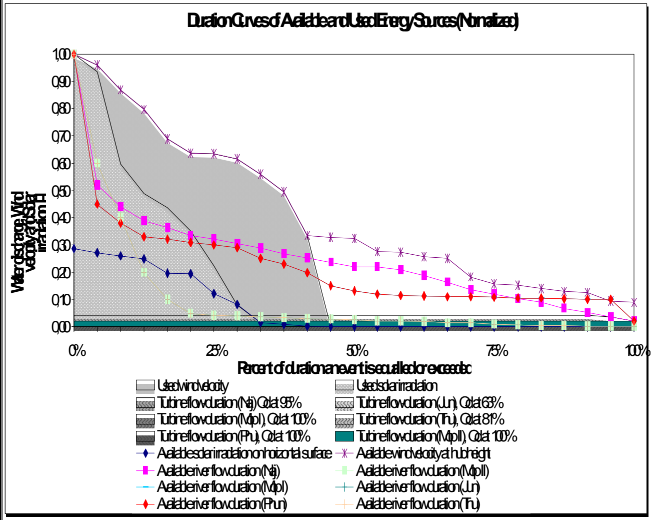
Junbesi Rural Electrification Project (JURE) Layout

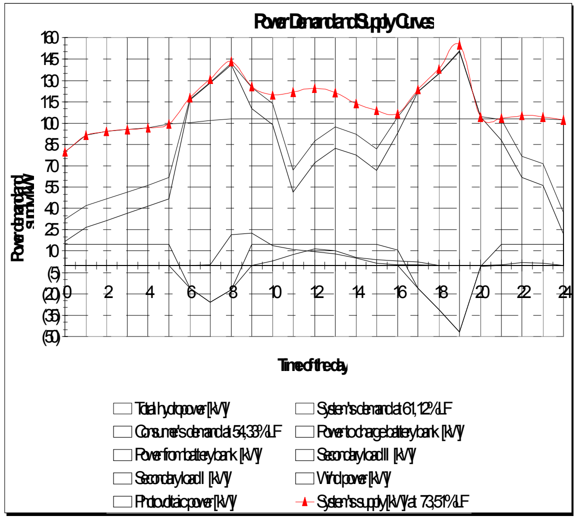
Electrical equivalent diagram of the JURE Project

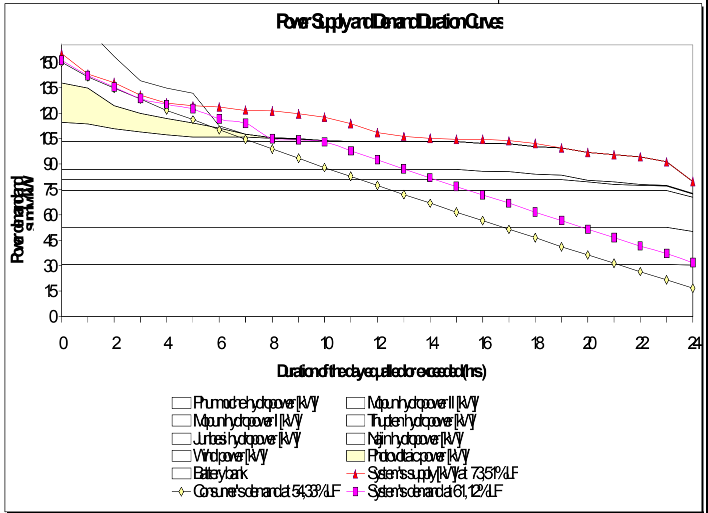
Boundary conditions

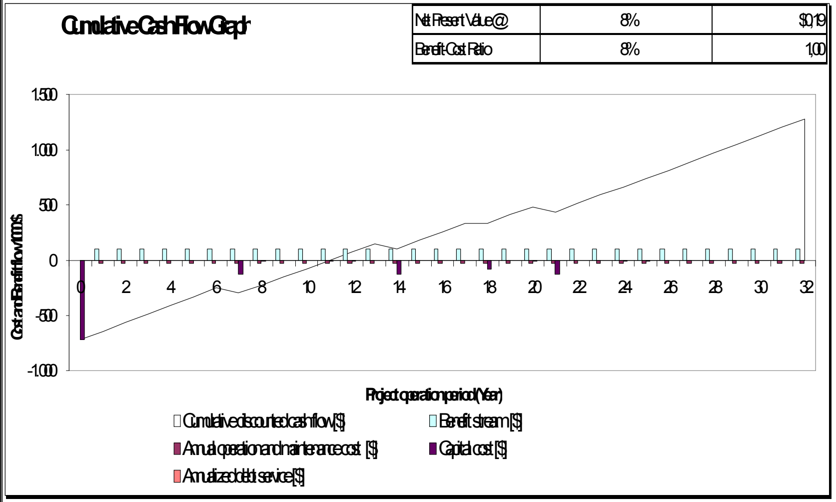
Check for system reliability preconditions:			Najin	Junbesi	Mopun (I)	Mopun (II)	Thupten	Phunmoche	Solar	Wind
Type of hydropower plant			Micro	Pico	Micro	Micro	Pico	Micro		
Water discharge/solar radiation/wind velocity	Q_A; S; v	[m³/s]; [W/m²]; [m/s]	0,021	0,090	0,220	0,220	0,033	0,202	3.241	9
Ecological flow	Q_{EC}	Yes=1; No=0	0	0	0	0	0	0		
Duty flow	Q_{DT}	Yes=1; No=0	0	0	0	0	0	0		
Flow ratio	m_0	[-]	0,4762	0,13	0,91	0,91	0,37	0,99		
Flow factor	m_T	[-]	1,00	1,00	1,00	1,00	1,00	1,00		
Check for turbine flow factor			Ok	Ok	Ok	Ok	Ok	Ok		
Maximum Power plants' installed capacity		[kW]	16,22	6,06	21,84	21,83	6,36	30,80	22,69	11,48
Gross head	H_G	[m]	118,50	10,00	15,00	15,00	27,00	26,00		
Net head over turbine	h_f	[m]	100,83	9,27	13,54	13,54	26,83	20,78		
Hydro-turbine diameter	$[D_T]$	[m]	0,11	0,31	0,45	0,45	0,11	0,37		
Suggested turbine type			Pelton	Cross-flow	Cross-flow	Cross-flow	Cross-flow	Cross-flow		
Maximum hydraulic losses in conduit	h_L	Calculated	15%	7%	10%	10%	1%	20%		
		Predefined	20%	10%	10%	10%	10%	25%		
Check for minimum head loss in conduit systems			OK	OK	OK	OK	OK	OK		
Minimum pipe thickness	t_{min}	[m]	0,007	0,009	0,01	0,01	0,01	0,008		
Proposed pipe thickness	t_D	[m]	0,04	0,01	0,01	0,01	0,01	0,01		
Check for minimum penstock thickness			OK	OK	OK	OK	OK	OK		
Calculated safety factor		[-]	5,74E+01	1,04E+01	5,07E+00	5,07E+00	2,38E+01	4,04E+00		
Recommended safety factor		[-]	2,50E+00	2,50E+00	2,50E+00	2,50E+00	2,50E+00	2,50E+00		
Check for Penstock structural safety			SAFE	SAFE	SAFE	SAFE	SAFE	SAFE		
Canal freeboard in unlined section	F	[m]	0,220	0,41	0,64	0,64	0,25	0,24		
Minmum canal freeboard	F_{min}	[m]	0,200	0,2	0,2	0,2	0,2	0,2		
Check for canal freeboard			SAFE	SAFE	SAFE	SAFE	SAFE	SAFE		
Calculated D_{PT}/d_{PT} ratio (only for Pelton)	D_{PT}/d_{PT}	[-]	9,74	-	-	-	-	-		
Recommended D_{PT}/d_{PT} ratio (only for Pelton)		[-]	9,00	9,00	9,00	9,00	9,00	9,00		
Check for D_{PT}/d_{PT} ratio (only for Pelton)			Ok	Ok	Ok	Ok	Ok	Ok		
Calculated specific speed (only for Pelton)	n_q	$[m^{-1}]$	7,93	-	-	-	-	-		
Recommended specific speed (only for Pelton)	n_q	$[m^{-1}]$	7,33	-	-	-	-	-		
Check for specific speed (only for Pelton)			Ok	Ok	Ok	Ok	Ok	Ok		
Critical limit condition of cavitation (for reaction turbine)	$h_{s,Cr}$	[m]	-	-	-	-	-	-		
Calcualted static head (for reaction turbines)	h_s	[m]	1,00	2,00	1,00	1,00	2,00	1,00		
Check for permissible static draft head			Ok	Ok	Ok	Ok	Ok	Ok		
Anemometer mounting height	H_{AM}	[m]				9,00				
Wind rotor hub height	H_{hub}	[m]				15,00				
Check for wind rotor mounting height						Ok				

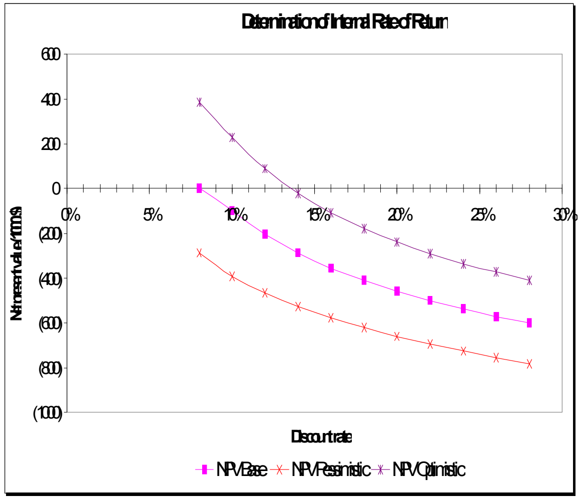
Constraints			Calculated	Predefined	Control	Excess	Objective function			Remarks
Min. battery state of charge	SOC_{min}	[kWh]	7,81	7,72	OK	0,09	Present value of cost	[$]	1167290,90	
Max. battery state of charge	SOC_{max}	[kWh]	244,53	154,42	OK	90,11				
Capacity balance	$P_P - (L'_C + L_L)$	[kW]	-0,15	0,00	Capacity ?	Penaulty ?	Cost of service	[$/kWha]	#DIV/0!	
Energy balance	$E_P - (E'_C + \cong E_L)$	[kWh]	-0,15	0,00	Capacity ?	Penaulty ?				
Max. System power supply	P_{max}	[kW]	155,06	160,00	OK		Net present value	[$]	0,19	
Max. System load	L_{max}	[kW]	155,06	160,00	OK					
Max. voltage drop	$\cong V$	[%]	0,66%	5%	OK	4,34%	Cumulative cash flow	[$]	1283177,17	
Max. grid power loss	$\cong P_{Tr}$	[%]	0,77%	5%	OK	4,23%				
Max. grid energy loss	$\cong E_{Tr}$	[%]	0,72%	5%	OK	4,28%	Benefit - Cost ratio	[-]	1,00	
Check for excess power	P_{ex}	[kW]	64,98	0,00	OK	64,98				
Check for excess energy	E_{ex}	[kWh]	522,88	0,00	OK	522,88	Simple payback	[Year]	9,22	
Check for installed capacity	$P_{inst} >= (L'_C + L_L)$	[kW]	150,85	155,06	OK	4,21				
Current carrying capacity	I_{max}	[A]	23,00	250,00	SAFE	227,00	System efficiency	[-]	80,89%	

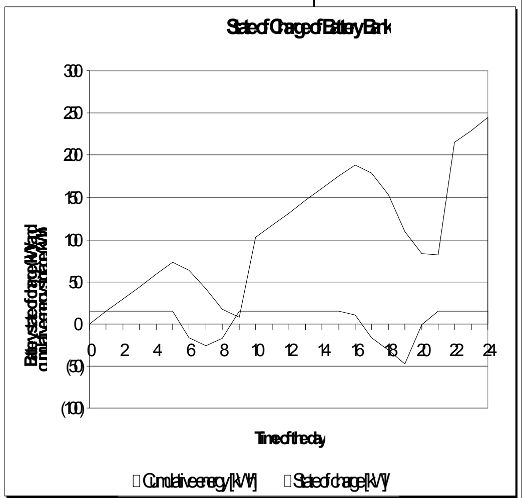

Duration Curves of Available and Used Energy Sources (Normalized)
Percent of duration an event is equalled or exceeded
Used wind velocity
Used solar irradiation
Available solar irradiation on horizontal surface
Available wind velocity at hub height


Power Demand and Supply Curves
Time of the day
Total hydropower [kW]
Consumer's demand at 54,33% LF
Power from battery bank [kW]
Secondary load I [kW]
Photovoltaic power [kW]
System's demand at 61,12% LF
Power to charge battery bank [kW]
Secondary load II [kW]
Wind power [kW]
System's supply [kW] at 73,51% LF


Power Supply and Demand Duration Curves
Duration of the day equalled or exceeded (hrs)
Wind power [kW]
Photovoltaic power [kW]
Battery bank
Consumer's demand at 54,33% LF
System's supply [kW] at 73,51% LF
System's demand at 61,12% LF


Cumulative Cash Flow Graph
Net Present Value @ | 8% | $0,19
Benefit-Cost Ratio | 8% | 1,00
Project operation period (Year)
Cumulative discounted cash flow [$]
Benefit stream [$]
Annual operation and maintenance cost [$]
Capital cost [$]
Annualized debt service [$]


Determination of Internal Rate of Return
Discount rate
NPV Base
NPV Pessimistic
NPV Optimistic


State of Charge of Battery Bank
Time of the day
Cumulative energy [kWh]
State of charge [kWh]

Results

Mini grid simulation		Najin			Junbesi			Mopun(I)			Thupten		Mopun[II]		Phurmoche		Control		
Node		1	2	3	4	5	6	7	8	9	10	11	7	12	13	14			
Branch		Najin HEP	P1-2	P2-3	P4-3	P5-4	P4-6	P7-6	P8-7	P7-9	P10-9	P11-10	0	P7-12	P13-12	P14-13	Load	Supply	Balance
Power flow	[kW]		16,2	9,2	2,8	6,1	-35,8	65,8	95,6	18,6	-8,6	6,4	0,0	0,2	5,8	30,8	155,1	155,1	0,0
Current flow	[A]		3,9	2,2	0,7	1,5	-8,6	15,8	23,0	4,5	-2,1	1,5	0,0	0,0	1,4	7,4			
Current carrying capacity	[A]		250,0	250,0	250,0	250,0	250,0	250,0	250,0	250,0	250,0	250,0	0,0	250,0	250,0	250,0			
Voltage drop at nodes	[V]		1,94	3,6	1,1	0,7	10,7	19,7	11,5	3,4	1,6	0,8	0,0	0,1	1,7	3,7			
Voltage drop at nodes	[%]		0,1%	0,1%	0,0%	0,0%	0,4%	0,7%	0,4%	0,1%	0,1%	0,0%	0,0%	0,0%	0,1%	0,1%			
Power loss	[W]		8,8	9,3	0,8	1,2	107,2	362,2	306,1	17,4	3,7	1,4	0,0	0,0	2,8	31,8	0,85		
Power loss	[%]		0,1%	0,1%	0,0%	0,0%	-0,3%	1%	0,3%	0,09%	0,0%	0,0%	0,0%	0,0%	0,0%	0,1%			
Node load	[kW]		7,0	12,0	0,0	39,1	30,0	0,0	11,0	10,0	0,0	15,0	0,0	6,0	0,0	25,0	155,1		
Node power plant	[kW]		16,2	0,0	0,0	6,1	0,0	0,0	95,6	0,0	0,0	6,4	0,0	0,0	0,0	30,8	155,1		
Line stretch factor	□		2,78	0,86	0,86	2,78	1,11	1,11	2,78	1,85	1,85	2,78	0,00	1,11	1,11	2,78	Difference	Load	Generator
Load connected		-16	7,00	12,00	34,00	-6,06	30,00	11,00	-95,62	10,00	15,00	-6,36		6,00	25,00	-30,80	-5,064	150,00	-155,06

Optimum System Configuration	Option	Base case			System's load factor		61,1%			
Power mix	Najin	Junbesi	Mopun (I)	Thupten	Mopun (II)	Phurmoche	Total Hydro	Solar power p	Wind power plants	
Capacity (kW)	16,2	6,1	21,8	21,8	6,4	30,8	103,1	22,7	11,5	137,3
Cumul. Energy [kWh]/day	382,2	113,5	523,1	523,0	138,6	739,1	2419,6	93,8	51,1	2564,5
Power rating for battery charge [kW]			14,6	46,9	Ok					
Energy stored in the battery [kWh]			244,5	154,4	Ok					
Additional battery charge			0,0	Original		Modified without ballast load				
Storage energy [kWh]			0,0	Demand	Supply	Demand	Supply			
Dumped load [kW]			0,0	150,0	125,80	150,85	155,064			
Dumped energy [kWh]			0,0	1956,0	2564,54	2212,9	2735,636			
Grid characteristics		**Control**		Excess	Deficit	Excess	Deficit			
Grid length [km]	12,25			80,4	-46,9	65,0	-0,15			
Size of conductor [mm²]	50,00			763,0	-154,4	522,877	-0,15			
Transmission voltage [kV]	3,00									
Maximum grid power loss [kW]	0,85000	0,85	Ok							
Maximum grid energy loss [kWh]	12,41	12,41	Ok							
Maximim voltage drop [V]	19,72									
Maximum current in the grid [A]	23,00									

System characteristics			Original	Modified daily demand			Modified daily supply	Excess		
Technical parameters	Symbol	Unit	Consumer's demand	Potentially salable demand	Dispatched power minus load not met	Modified demand including transmission loss without ballast load	Modified supply	Maximum secondary power & energy reserve	Control	Remarks
Maximum load/power	L_{max}; P_{max};P_{res}	[kW]	150,00	150,00	150,00	150,85	155,06	64,98	Ok	
Minimum load/power	L_{min}; $P_{min;}$	[kW]	17	17	17	32	80	0,00	Ok	
Average load/power	L_{avr}; P_{avr}	[kW]	79	79	79	90	113	23,17	Ok	
Daily energy	E_C; E_P	[kWh]	1956	1956	1956	2212,91	2735,64	522,88	Ok	
Load ratio	$m_{0,C,sys;}m_{0,P,sys}$	[%]	11%	11%	11%	21%	51,4%	0,00%		
System's load factor	$m_{C,sys;}$ $m_{P,sys}$	[%]	54,3%	54,33%	54,33%	61,12%	73,51%	73,51%	Ok	
System's plant factor	n_{sys}	[%]	52,6%	52,56%	52,55%		59,46%	59,46%	Ok	
Load/plant utilization hour	$T_{m,sys}$; $T_{n,sys}$	[hrs.]	13,04	13,04	13,04	14,67	14,271	17,64	Ok	
System's efficiency	$_{sys}$	[%]	71%	71,50%	71,49%	80,89%				
System improvement ratio	SIR	[%]				1,1	97,28%	97,28%	Ok	Index for plant utilization
Energy index of reliability	EIR	[%]				99,99%	1,03	1,03	Ok	Reserve factor
Max. transmission line efficiency	$_{Tr}$	[%]	713926,193	713926,1927	713872,87	99,45%	5209	5354	Ok	
Annual energy			713926,19	713926,193	713872,87	Control	807711	807711	Ok	Annual Energy

Optimized size	Installed			Net power and energy			Cost of project components			
Components	Installed capacity (kW)	Total annual energy (kWh)	Annual plant utilization hour	Net peak power output	Net annual energy output	Maximum transmission line efficiency	Total construction cost [$]	Operation and Maintenance [$/a]	Replacement cost	Total without subsidy
Najin hydropower plant	16	139496	8599				38022,89	2533,47	1901,14	
Junbesi hydropower plant	6	41445	6839				17154,74	1143,02	857,74	
Mopun I hydropower plant	22	190933	8743	154,21	993977		44706,55	2978,80	2235,33	
Mopun II hydropower plant	22	190893	8743				44698,91	2978,29	2234,95	
Thupten hydropower plant	6	50603	7951				22194,45	1478,82	1109,72	
Phunmochhe hydropower plant	31	269774	8759				86115,04	5737,85	4305,75	
Photovoltaic power plant	23	34250	1510	0	0		111150,77	1111,51	77805,54	
Wind power plant	11	18661	1625	0	0		34450,54	344,51	6890,11	
Primary load II (Battery bank)	52	56363	1085	0	0		155821,86	4674,66	124657,49	
Deferable load I (Machines)	0	0	0	0	0		0,00	0,00	0,00	
Differable load II (Pump)	0	0	0	0	0		0,00	0,00	0,00	
Differable load III (Ballast)	0	0	0				0,00	0,00	0,00	
Transmission loss	0,853	(4530)					111622,00	1116,22	2232,44	
Total	189	992419		154,2115	993977	99,45%	665937,75	20420,63	221471,32	665937,75

Economic parameters	Financial parameters		Remarks

Economic parameters			Financial parameters						Remarks	
Discount rate	%	8%	Debt ratio	%	0%	Income tax	%	0%		
Excalation rate	%	0%	Debt interest rate	%	0%					
Inflation rate	%	0%	Debt term	Year	0					
Economic project life	Year	32	Capital recovery factor	[-]	1,0000					

Economic feasibility	Amount	Unit
Initial investment	$719.212,77	[$]
First year distribution	$719.212,77	[$]
Second year distribution	$0,00	[$]
Present value cost	$1.167.290,90	[$]
Present value of benefit	$1.167.291,08	[$]
Net present value	$0,19	[$]
Cumulative NPV	$1.283.177,17	[$]
Year to positive cash flow	3878788,18	[Year]
Simple payback	9,22	[Year]
Benefit-Cost ratio	1,00	[-]
Profitability index	0,00	[-]
Debt service coverage	#DIV/0!	[-]
Subsidy		[$]

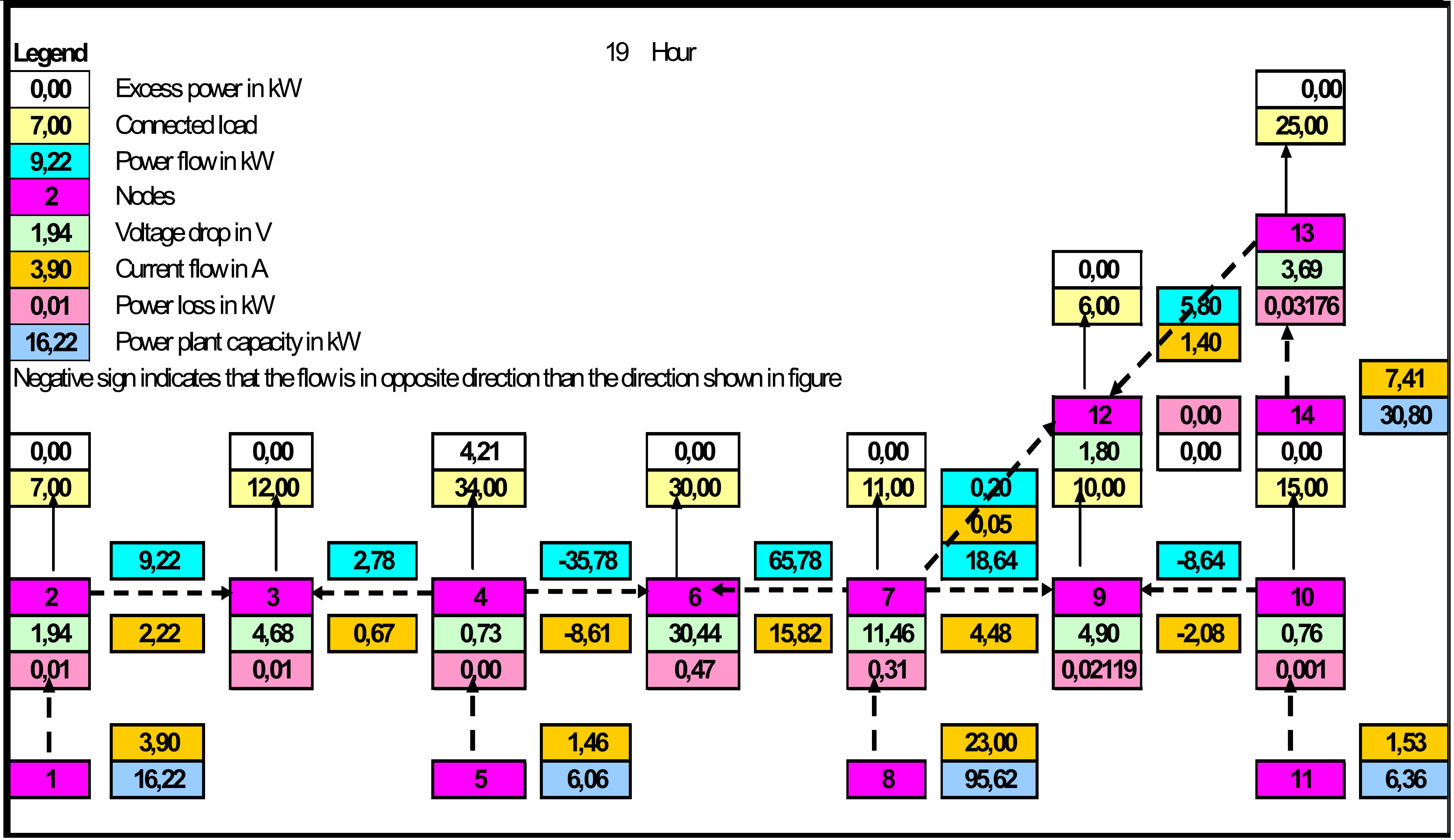
Financial feasibility		Amount	Unit
Annual cost			
Annual operation and maintenance		24.097,12	[$/a]
Annual debt service		#DIV/0!	[$/a]
	Annual cost- Total	#DIV/0!	[$/a]
Annual revenue			
Annual energy revenue		102.080,55	[$/a]
Annual capacity revenue			[$/a]
	Annual revenue- Total	102.080,55	[$/a]
Breakeven energy value/Avoided cost of energy		0,15	[$/kWh]
Project equity		719212,77	[$]
Project debt		$0,00	[$]
Debt payments		#DIV/0!	[$/a]
Cost of service		#DIV/0!	[$/kWh]
Value of energy		0,15	[$/kWh]
Difference in energy value		#DIV/0!	[$/kWh]

Scenarios for various energy input variables						
Power coverage curve	yes					
Salable load+penaulty	Power	150				
	Energy sale	713873				
Wind	**25**					
Wind velocity	8,27					
Solar	**18**					
Solar radiation	922,92					
Hydro Site	Najin	Junbesi	Mopun I	Mopun II	Thupten	Phunmoche
FDC	**3**	**9**	**1**	**1**	**9**	**1**
Water discharge	0,004	0,1	0,2	0,22	0,03	0,2

Sensitivity Analysis	Pesimistic	Optimistic	IRR
Investment increase	**10%**		**8%**
Investment decrease		**10%**	**10%**
Benefit increase		**10%**	**12%**
Benefit decrease	**10%**		**14%**
O & M increase	**10%**		**16%**
O & M decrease		**10%**	**18%**
Interest increase	**10%**		**20%**
Interest decrease		**10%**	**22%**
Econ. Life increase		**10%**	**24%**
Econ. Life decrease	**10%**		**26%**
R & R cost increase	**10%**		**28%**
R & R cost decrease		**10%**	

B. Appendix II: Mini-Grid Characteristics

				Najin			Junbesi			Mopun			Thupten		Mopun		Phunmoche	Total
Grid characteristics		**Nodes**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**7**	**12**	**13**	**14**	**Total**
Length of transmission branch				**0,50**	**1,63**	**1,63**	**0,50**	**1,25**	**1,25**	**0,50**	**0,75**	**0,75**	**0,50**		**1,25**	**1,25**	**0,50**	12,25
Length of transmission branch	lst	[km]		0,50	1,63	1,63	0,50	1,25	1,25	0,50	0,75	0,75	0,50		1,25	1,25	0,50	12,25
Area of the conductor	A	[mm²]	50,00															
Nominal phase voltage	U_N	[kV]	3,00															
System's power factor	Cos	[-]	0,80															
phase angle		[deg.]	36,87															
Type of transmission line		3-phase																
System frequency	f	[Hz]	60,00															
Type of conductor	Cu	56,00	cu															
	Al	35,00																
Reference conductivity	20	[m/Ohm mm²]	56,00															
Conductor temperature	T	[°C]	40,00															
Thermal coeff.	20	[K-1]	0,0040															
Conductor spacing	d	[mm]	900,00															
Induction constant	m_o	[H/m]	0,0002															
Number of conductors in a bundle		n	1,00	[-]														
Current carrying capacity (for Cu, after DIN 48201)			250,00	[A]	Back to SystConf.			Back to Home										
Current carrying capacity (for Al, after DIN 48204)			210,00															
Grid				Najin			Junbesi			Mopun			Thupten		Mopun		Phunmoche	Total
Node			1	2	3	4	5	6	7	8	9	10	11	7	12	13	14	
Pmax		kW	16,00	7,00	12,00	34,00	6,00	30,00	11,00	92,00	10,00	15,00	6,00		6,00	25,00	30,00	0,00
Pmin		kW	16,00	1,08	1,85	5,24	6,00	4,62	1,69	92,00	1,54	2,31	6,00		0,92	3,85	30,00	
mo		[-]	1,00	0,15	0,15	0,15	1,00	0,15	0,15	1,00	0,15	0,15	1,00		0,15	0,15	1,00	
Pav		kW	16,00	2,08	3,56	10,10	6,00	8,91	3,27	92,00	2,97	4,46	6,00		1,78	7,43	30,00	
m		[-]	1,00	0,30	0,30	0,30	1,00	0,30	0,30	1,00	0,30	0,30	1,00		0,30	0,30	1,00	
Nodes			1	2	3	4	5	6	7	8	9	10	11	7	12	13	14	
Length of stretch	lst	[km]		0,50	1,63	1,63	0,50	1,25	1,25	0,50	0,75	0,75	0,50		1,25	1,25	0,50	12,25
Area of the conductor	A	[mm²]		50,00	50,00	50,00	50,00	50,00	50,00	50,00	50,00	50,00	50,00		50,00	50,00	50,00	
Nominal phase voltage	U	[kV]	3,00	3,00	3,00	3,00	3,00	3,00	3,00	3,00	3,00	3,00	3,00		3,00	3,00	3,00	
System's power factor	Cos	[-]		0,80	0,80	0,80	0,80	0,80	0,80	0,80	0,80	0,80	0,80		0,80	0,80	0,80	0,90
phase angle		[deg.]		36,87	36,87	36,87	36,87	36,87	36,87	36,87	36,87	36,87	36,87		36,87	36,87	36,87	
System frequency	f	[Hz]		60,00	60,00	60,00	60,00	60,00	60,00	60,00	60,00	60,00	60,00		60,00	60,00	60,00	
Type of conductor		cu																
Reference conductivity	20	m/Ohm mm²		56,00	56,00	56,00	56,00	56,00	56,00	56,00	56,00	56,00	56,00		56,00	56,00	56,00	
Conductor temperature	T	°C		40,00	40,00	40,00	40,00	40,00	40,00	40,00	40,00	40,00	40,00		40,00	40,00	40,00	
Thermal coeff.	20	K^{-1}		0,0040	0,0040	0,0040	0,0040	0,0040	0,0040	0,0040	0,0040	0,0040	0,0040		0,0040	0,0040	0,0040	
Conductivity		m/Ohm mm²		51,85	51,85	51,85	51,85	51,85	51,85	51,85	51,85	51,85	51,85		51,85	51,85	51,85	
Conductor spacing	d	mm		900,00	900,00	900,00	900,00	900,00	900,00	900,00	900,00	900,00	900,00		900,00	900,00	900,00	
Geometrical average of distan	d_{gmi}	mm		1133,93	1133,93	1133,93	1133,93	1133,93	1133,93	1133,93	1133,93	1133,93	1133,93		1133,93	1133,93	1133,93	
Induction constant	m_o	H/m		0,0002	0,0002	0,0002	0,0002	0,0002	0,0002	0,0002	0,0002	0,0002	0,0002		0,0002	0,0002	0,0002	
Reactance	X_L	Ohm/km		0,4448	0,4448	0,4448	0,4448	0,4448	0,4448	0,4448	0,4448	0,4448	0,4448		0,4448	0,4448	0,4448	
Resistance	R_L	Ohm/km		0,38571	0,39	0,39	0,39	0,39	0,39	0,39	0,39	0,39	0,39		0,39	0,39	0,39	
Line impedance	y	Ohm/km		0,71934	0,71934	0,72	0,72	0,72	0,72	0,72	0,72	0,72	0,72		0,72	0,72	0,72	
Results:																		
Load element				L1-2	L2-3	L4-3	L5-4	L4-6	L7-6	L8-7	L7-9	L10-9	L11-10		L7-12	L13-12	L14-13	
Line stretch factor (Admitance	a	S or [Ohm-1]		2,78	0,86	0,86	2,78	1,11	1,11	2,78	1,85	1,85	2,78		1,11	1,11	2,78	
				2,00	3,00		4,00	6,00		7,00	9,00		10,00		12,00		13,00	
Branch				P1-2	P2-3	P4-3	P5-4	P4-6	P7-6	P8-7	P7-9	P10-9	P11-10		P7-12	P13-12	P14-13	Load
Power flow	[kW]			6,95	5,95	-3,95	0,45	-46,46	49,46	39,71	1,46	0,04	2,04		-27,84	28,84	30,59	79,73
Current flow	[A]			1,67	1,43	-0,95	0,11	-11,18	11,90	9,55	0,35	0,01	0,49		-6,70	6,94	7,36	11,90
Corrected current flow	[A]																	
Maximum current carrying ca	[A]			250,00	250,00	250,00	250,00	250,00	250,00	250,00	250,00	250,00	250,00		250,00	250,00	250,00	
Voltage drop at nodes	[V]			0,83	2,32	-1,54	0,05	13,93	14,83	4,76	0,26	-0,01	0,24		-8,34	8,64	3,67	14,83
Voltage drop at nodes	[%]			0,03%	0,08%	-0,05%	0,00%	0,46%	0,49%	0,16%	0,01%	0,00%	0,01%		-0,28%	0,29%	0,12%	0,49%
Power loss	[kW]			1,62	3,86	1,7007	0,01	180,70	204,78	52,80	0,11	0,00	0,14		64,86	69,60	31,32	0,6115
Power loss	[%]			0,02%	0,06%	-0,04%	0,00%	-0,39%	0,41%	0,13%	0,01%	0,00%	0,01%		-0,23%	0,24%	0,10%	0,00%
Node load	[kW]			1,00	2,00		50,86	3,00		16,62	1,50		2,00		1,00		1,75	79,73
Node power plant	[kW]			6,95			0,45			39,71			2,04				30,59	79,73


Legend
19 Hour
0,00 Excess power in kW
7,00 Connected load
9,22 Power flow in kW
2 Nodes
1,94 Voltage drop in V
3,90 Current flow in A
0,01 Power loss in kW
16,22 Power plant capacity in kW
Negative sign indicates that the flow is in opposite direction than the direction shown in figure
0,00
25,00
13
3,69
0,03176
0,00
6,00
5,80
1,40
7,41
30,80
12
1,80
10,00
0,00
0,00
14
0,00
15,00
0,00
7,00
0,00
12,00
4,21
34,00
0,00
30,00
0,00
11,00
0,20
0,05
18,64
9,22
2,78
-35,78
65,78
-8,64
2
1,94
0,01
3
4,68
0,01
4
0,73
0,00
6
30,44
0,47
7
11,46
0,31
9
4,90
0,02119
10
0,76
0,001
2,22
0,67
-8,61
15,82
4,48
-2,08
3,90
16,22
1,46
6,06
23,00
95,62
1,53
6,36
1
5
8
11

CURRICULUM VITAE

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1964 - 1969	Bhanu Morang Primary School, Biratnagar, Nepal.
1970 - 1975	Aadarsha Multipurpose High School, Biratnagar, Nepal
1976 - 1977	Intermediate of Science, Mahendra Morang College, Biratnagar, Nepal

Higher Education :

1977 - 1979	**Certificate level in Electrical Engineering** (with Merit), Institute of Engineering, Tribhuwan University, Nepal.
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Nepal Hydropower Association

German-Nepal Friendship Association

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