

A Study of Remote Area Internet Access with Embedded Power Generation

Manisa Pipattanasomporn

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Dr. Saifur Rahman, Chair

Dr. Luiz A. DaSilva

Dr. Lamine Mili

Dr. Sanjay Jain

Dr. Paviz Ghandforoush

Dr. Michael Willingham

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(ABSTRACT)

This study presents a methodology and the necessary analytical tools to evaluate the alternatives to provide Internet access with embedded power generation in remote areas. The objective is to provide a screening tool for policy makers to analyze possible telecom and power alternatives. Results from the study demonstrate the technical alternatives to providing sustainable Internet and power access. The dissertation investigates innovative telecom technologies currently available on the market, and develops a model that generates a Telecom-and-Internet access map of a region or a small country. The map illustrates the combination of technologies and their locations that can provide wide-area Internet access to cover a majority of the population at the least cost. The model then looks at the design of a small-scale power system for a remote location where grid power is unavailable or unreliable. The methodology takes into account locally available energy resources, technical and economic parameters of each power generating technology, and the trade-off among investment costs, environmental costs and system robustness. Lastly, a computer simulation is conducted to verify that the power system design has the ability to meet the demand at the level of required reliability.

A remote area of a developing country (Chittagong and Chittagong Hill Tracts – Bangladesh) is selected as a case study. Several scenarios are simulated in order to explore the possibility of extending the reach of the Internet and electric power to the remote area, and to conceptualize pilot projects as building blocks to build a countrywide infrastructure. Since the selected area is one of the least developed and most difficult to access in Bangladesh, demonstrating that the Internet and local power access can be provided to this area can serve as a model for similar places around the world.

Table of Contents

Abstract	ii
Table of Contents	iii
List of Figures	vi
List of Tables.....	viii
Acknowledgements	ix
Glossary.....	x
PART I: INTRODUCTION	1
Chapter 1 Introduction	2
1.1 The Internet for Developing Nations.....	2
1.2 Facts and Rationale.....	3
1.3 Main Focus and Scope of the Dissertation	4
1.4 Contributions	5
1.5 Organization of Dissertation.....	6
Chapter 2 Literature Review.....	8
2.1 Telecommunication Systems for PSTN Access	8
2.2 Distributed Power Generation Technologies.....	11
2.3 The Design of Telecommunication Infrastructure.....	13
2.4 The Design of Hybrid Energy Systems	13
2.5 Conclusions	18

PART II: METHODOLOGY.....	19
Chapter 3 Telecommunication Model	20
3.1 Model Concept and Key Assumptions	20
3.2 Structure of Telecommunication Model.....	21
3.3 Formulation of the Optimization Model.....	25
3.4 Conclusions	29
Chapter 4 Hybrid Energy System Model.....	30
4.1 Structure of the Power Model.....	30
4.2 Hybrid Energy System Configuration.....	31
4.3 System Component and Modeling	33
4.4 Optimization Problem	37
4.5 Conclusions	42
Chapter 5 Computer Algorithm for the Verification of Power Solutions.....	43
5.1 Dispatch Concepts	43
5.2 Analysis of Possible Dispatch Strategies.....	44
5.3 Implemented Dispatch Algorithm	45
5.4 Conclusions	50
PART III: A CASE STUDY OF A DEVELOPING COUNTRY.....	51
Chapter 6 Country Background and Choice of Technologies.....	52
6.1 Basic IT infrastructures in Bangladesh.....	52
6.2 Identifying Network Gap.....	54
6.3 Comparison of Alternate Technologies.....	55
6.4 Need for Upgrading the National Backbone	56
6.5 Conclusions	58

Chapter 7 Expanding Country-Wide Internet Access	59
7.1 Technology and Cost Assumptions	59
7.2 Model Implementation with a Case Study of Bangladesh.....	61
7.3 Case Studies of Bangladesh.....	64
7.4 Conclusions	68
Chapter 8 Power Solutions for Telecenter Kiosks.....	70
8.1 Demand and Supply Assumptions.....	70
8.2 Model Implementation	74
8.3 Power Solutions for a High-Demand Telecenter.....	75
8.3 Power Solutions for a Low-Demand Telecenter	78
8.4 Verification of Results.....	81
8.5 Conclusions	82
Chapter 9 Conclusions and Recommendations	83
9.1 Conclusions	83
9.2 Suggestions for Variations in Model Implementation and Future Research	85
Appendix – A Electrolysis vs Reformer.....	86
Appendix – B Costs of Alternate Telecommunication Technologies	89
Appendix – C Optical Fiber Routes for the Three Case Studies	90
Appendix – D Determination of Inverter Efficiency.....	93

List of Figures

Fig. 1. Technology choices for PSTN access	8
Fig. 2. Telecommunication optimization model.....	22
Fig. 3. The arc UV intersects the arc PQ at point A	23
Fig. 4. (a) An element P_{cd} ; and (b) an element E_{cd}	27
Fig. 5. (a) An element $A_{1, cd}$ for base station B1; (b) an element $A_{2, cd}$ for the base station B2.....	28
Fig. 6. A network with one source node, one destination node, and four transshipment nodes....	28
Fig. 7. Power Optimization Model	31
Fig. 8. The configuration of a hybrid energy system.....	32
Fig. 9. An actual power curve of AIR403 and the modeled power curve	34
Fig. 10. Efficiency and fuel consumption characteristics of IC engines based on DNAC 50Hz ..	35
Fig. 11. Efficiency and fuel consumption characteristics of PEM fuel cells.....	36
Fig. 12. Hybrid system controller block diagram.....	43
Fig. 13. Dispatch algorithm: Part I	46
Fig. 14. Algorithm to check SOC	47
Fig. 15. Dispatch algorithm: Part II	48
Fig. 16. Definition of V_t	49
Fig. 17. Algorithm to determine V_t	50
Fig. 18. Network gap in Chittagong and Chittagong Hill Tracts.....	54
Fig. 19. Break-even line of the cost to extend optical fiber vs the cost of a VSAT system	57
Fig. 20. Break-even line comparing length of optical fiber vs months in operation of VSAT	57
Fig. 21. Extraction of population density data with C++	62
Fig. 22. Calculation of population density	63
Fig. 23. Political boundary and selected areas.....	64
Fig. 24. A Telecom-and-Internet access map for 50% Internet coverage	65

Fig. 25. A Telecom-and-Internet access map for 70% Internet coverage	66
Fig. 26. A Telecom-and-Internet access map for 90% Internet coverage	67
Fig. 27. Demand for low-demand and high-demand telecenters on weekdays	71
Fig. 28. Summary of 20-year LCC per kWh for a high-demand telecenter without externalities	76
Fig. 29. Summary of 20-year LCC per kWh for a high-demand telecenter with externalities.....	77
Fig. 30. Summary of 20-year LCC per kWh for a low-demand telecenter without externalities.	79
Fig. 31. Summary of 20-year LCC per kWh for a low-demand telecenter with externalities.....	80

List of Tables

Table 1. ITU Asia-Pacific telecommunications indicator 2003	4
Table 2. Optical fiber standard and data rate.....	53
Table 3. Cost of ownership at different levels of remoteness	56
Table 4. Component costs and economic assumptions	60
Table 5. Power consumptions for various end-use appliances	70
Table 6. Solar insolation and wind speed from VTSTF as of 2001	72
Table 7. Cost and specification of each generating technology at 24V.....	73
Table 8. Fuel consumption characteristics of IC engines and PEM fuel cells	73
Table 9. Externality costs and emission factors for NO _x , SO ₂ , CO ₂ and PM-10	74
Table 10. Resource description	74
Table 11. Summary of power solutions for a high-demand telecenter when EENS = 0%.....	75
Table 12. Summary of power solutions for a high-demand telecenter when EENS = 0%.....	78
Table 13. Verification of unmet demand of PV-BT systems	81

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Glossary

a_j	:	Availability of generating unit j .
$avai_j$:	Yearly availability of generating unit j .
$[A_{i,cd}]$:	Coverage matrix, size c by d , associated with base station i , location (c, d) .
AH	:	Amp-Hour of battery.
b_i	:	$b_i > 0$ for source nodes; $b_i < 0$ for destination nodes; $b_i = 0$ for transshipment nodes.
C_f	:	Fuel cost (\$/l).
C_j	:	Summation of discounted capital costs of generating unit j (\$).
DoD	:	Depth of discharge.
E_0	:	Solar intensity at the standard test condition (1000 W/m ²).
E_{ysi}	:	Solar intensity in any year y , season s , and hour i .
EF_{jm}	:	Emission factor of technology j , emission type m (lb/kWh).
$[E_{cd}]$:	The element E_{cd} in the matrix $[E_{cd}]$ is 1 if the location (c, d) is in the coverage area of at least one selected base station; the element E_{cd} is 0 otherwise.
F_{j0}	:	Fuel consumption rate at no load (l/h) of generating unit j .
F_{jt}	:	Incremental fuel consumption rate (l/kWh) of generating unit j .
F_{jysi}	:	Fuel consumption rate (l/h) of generating unit j in year y , season s , and hour i .
$load_{ysi}$:	Load in hour i , season s , year y (kWh/hr).
$LOLP$:	Loss of load probability.
M	:	Any large number.
n	:	Total number of nodes in the network.
OM_{jysi}	:	Operation and maintenance cost of generating unit j (\$/kWh).

P_j	:	Unit size of generating unit j (kilo watts or watts or AH).
$[P_{cd}]$:	Population matrix, each element P_{cd} in this matrix represents population associated with an area (c, d) .
r	:	Coverage distance (km).
R	:	Required reliability level (%).
S_j	:	Discounted salvage value of generating unit j (\$).
S	:	Slag variable to capture deficit energy (kWh/hr).
SOC_i	:	Battery stage of charge in hour i .
SOC_{min}	:	Minimum allowable battery state of charge.
SOC_{max}	:	Maximum allowable battery state of charge.
T_c	:	Temperature coefficient.
T_{ysi}	:	Ambient temperature in year y , season s , hour i (C°).
U_{jysi}	:	The generation from generating unit j in year y , season s , hour i (kW in one hour).
$U_{j=PV}^{jysi}$:	Total energy produced from PV in hour i (kWh/hr).
$U_{j=PV}^{jysi,load}$:	Energy produced from PV in hour i , routed to load (kWh/hr).
$U_{j=PV}^{jysi,batt}$:	Energy produced from PV in hour i , routed to battery (kWh/hr).
$U_{j=diesel}^{jysi}$:	Total energy produced from diesel generator in hour i , season s , year y (kWh/hr).
$U_{j=diesel}^{jysi,load}$:	Energy produced from diesel generator in hour i , season s , year y , routed to load (kWh/hr).
$U_{j=diesel}^{jysi,batt}$:	Energy produced from diesel generator in hour i , season s , year y , routed to battery (kWh/hr).
$U_{batt, in}$:	Energy input to the battery.
$U_{batt, load}$:	Energy generated from the battery to the load.

- $\sum_{j=ACsources} U_{jysi,batt}$: Total energy produced from all AC sources in hour i , season s , year y , routed to the battery (kWh/hr).
- $\sum_{j=DCsources} U_{jysi,batt}$: Total energy produced from all DC sources in hour i , season s , year y , routed to the battery (kWh/hr).
- $\sum_{j=ACsources} U_{jysi,load}$: Total energy produced from all AC sources in hour i , season s , year y , routed to the load (kWh/hr).
- $\sum_{j=DCsources} U_{jysi,load}$: Total energy produced from all DC sources in hour i , season s , year y , routed to the load (kWh/hr).
- V_{sys} : DC system voltage (volts).
- WS_{ysi} : Wind speed in year y , season s , hour i .
- X_j : Integer decision variables, representing the number of generating units j .
- X_i : Integer decision variable – a decision to install wireless technology at node i .
- y_{ij} : A directional flow to arc ij .
- Y_{ij} : Integer decision variable – a decision to lay fiber along arc ij .
- η_{inv} : Inverter efficiency.
- α_i : Costs of wireless base stations installed at node i ; these costs are the cost of a base station and the cost of a tower.
- θ_{ysi} : Hours of operation of hour i , in season s , in year y (hours).
- α_m : Externality cost of emission type m (\$/lb).
- δ_j : Discounted fuel costs of generating unit j (\$/liter for diesel oil and \$/BTU for natural gas).

PART I: INTRODUCTION

Chapter 1

Introduction

1.1 The Internet for Developing Nations

Over several decades, rural electrification has been recognized as a powerful tool that increases the living standards in poor and remote communities. But it was not until recently that the Internet has been widely believed to be a key for social and economic development. With electric power as a prerequisite, the Internet can significantly enhance the quality of life for the rural citizen by enabling access to information, as well as, opening up new opportunities for distance education, health care, trade, and leisure activities.

Considerable evidence in support of the above statement has been gathered through examples in remote communities in certain developing countries. In the village of T. Pudupatti, India, a villager emailed government veterinary officials to inquire about the dying of hens in the village [1]. This email resulted in a visit from veterinary representatives to vaccinate all hens. In Ulagu-pitchanpatti district, India, a kiosk operator used her webcam to take a picture of one of the diseased plants, then emailed it to a scientist at a regional agricultural collage. The scientist got back to her with a proposed remedy [2]. In Madhya Pradesh, India, a person can go to the kiosk and have access to a variety of local data, including information about the district, up-to-date market prices of crops and livestock, weather reports and a village newspaper. E-government services are also provided, including access to a host of local government services, i.e. driving license applications, registration of births and deaths, application for income, caste and domicile certificates, and public complaints. Other available services are bus and railway timetables, telephone directory, information on ambulance service, and job vacancies [3]. In Sri Lanka, farmers used newly installed telephones to find out the prices of coconut, fruit and other produce in Colombo. Instead of selling their crops at fifty to sixty percent of the Colombo price, the farmers were able to get between eighty and ninety percent [4].

These examples demonstrate that the Internet can play a major role in the advancement of the quality of rural life in developing nations. In fact, the Internet has been expanding rapidly in the past several years, as shown by the following instances of expanding Internet usage in remote villages in developing countries. Amader Gram Knowledge Center [5] in Bangladesh is a project of integrated rural development that acts as a new model for information retrieval and storage,

and which aims to develop a learning system at the grass-root level using the Internet. In the North Eastern states of India, the federal government has set up satellite-based Internet connectivity for inaccessible and low economic development areas, called Community Information Centers (CICs) [6]. There are more than 450 CICs across this region as of 2004. The purpose of this project is primarily for remotely administered lectures, online course and virtual laboratory. Another example is the World Links project [7], which aims to improve educational and economic opportunities for youth in developing countries through the use of technology and the Internet. The World Links implements its program to over 1,400 schools and communities in 30+ countries in Africa, the Middle East, Asia, Latin America, and Eastern Europe.

1.2 Facts and Rationale

Although the broad benefits of the Internet have long been established and several attempts have been initiated to integrate the Internet into the developing world, Internet connection in developing countries remains infinitesimal. The least developed countries have a share of less than 5 Internet users per 10,000 population. This number is confirmed by the figures from ITU (International Telecommunication Union in 2003), which indicate the landline telephone and cellular mobile subscribers per 100 inhabitants and Internet users per 10,000 inhabitants as shown in Table 1.

There are many explanations for such sluggish penetration of the Internet regardless of the evidence that it could tremendously improve quality of every rural life. Several obvious characteristics of remote areas make it unprofitable for service providers to develop necessary telecommunication infrastructures. These factors include low income residents, scattered settlements of villages, severe geographical or topographical conditions, and partial or total lack of public services such as access roads and regular transport facilities. In order for a telecommunication project to be successful, it must be provided to an area that has an adequate existing Internet backbone and transportation infrastructures, and is densely populated and developed enough to justify the investment decision.

A primary barrier to Internet penetration in rural areas is the lack of the most important element to support the operation of the Internet, namely, electricity. At present, roughly two billion out of six billion people in the world do not have access to electricity. In order for the Internet to be usable and sustained over the long period of time, reliable local power supply first must be provided. In addition, suitable applications must be developed and made available to local residents. Once these ingredients are in place, an overall improvement in education, employment, literacy rate, economic activities, market access, and health care should result.

Table 1. ITU Asia-Pacific telecommunications indicator 2003

Countries	GDP per capita (US\$) 2002	Main Telephone Lines per 100 inhabitants	Cellular Mobile Subscribers per 100 inhabitants	Internet Users per 10,000 inhabitants
Africa				
Angola	715	0.67	0.93	29.42
Benin	413	0.95	3.36	99.64
Burundi	89	0.34	0.90	19.67
Cameroon	670	0.70	6.62	37.90
D.R. Congo	143	0.02	1.89	9.50
Ethiopia	96	0.63	0.14	10.81
Nigeria	409	0.69	2.55	60.82
Tanzania	282	0.42	2.52	70.80
Uganda	243	0.24	3.03	48.83
Asia				
Bangladesh	352	0.55	1.01	17.98
Cambodia	254	0.26	2.76	24.75
China	963	20.92	21.40	632.48
India	494	4.63	2.47	174.86
Myanmar	148	0.72	0.13	5.64
Nepal	237	1.57	0.21	34.48
Philippines	969	4.17	19.13	440.38
Sri Lanka	863	4.65	4.92	117.41
Thailand	2,044	10.55	26.04	1,105.19

Source: International Telecommunication Union (ITU) in 2003

1.3 Main Focus and Scope of the Dissertation

This dissertation develops a computer model that can be used as a screening tool for policy makers and planners in both the telecom and regulatory agencies to filter various technologies for enabling sustainable and affordable last-mile Internet and power access in remote communities. In order to complete this objective, the following specific tasks are necessary.

1. The development of an optimization model to identify opportunity for wide-area Internet access: a computer model is developed to produce a Telecom-and-Internet access map of a region or a small country. This map suggests the number and location of wireless base stations, as well as the least expensive route to extend Internet backbone with fiber optic cable, in order to provide wide-area Internet access to cover a given percent of the total population in the area at the lowest initial cost. Major inputs to the model include Geographic Information System (GIS) data of political boundary, existing telecom infrastructure, railway and highway networks, population density, as well as cost and performance of the selected telecom technology.

2. The development of an optimization model to help in the design of a small-scale power supply system: a computer model is developed in order to help in the design of an optimal power supply

configuration for a community center. The model evaluates system life cycle costs, environmental costs, and maintenance of system reliability based on a specified requirement. Important information required includes hourly solar and wind resources, price of fossil fuels, technical and economic characteristics of each technology, reliability requirement, demand characteristics, and environmental cost. The dissertation does not use the model to determine the power solution for the base station. This is because the base station is generally located along transportation infrastructures, closed to the public switch telephone network (PSTN), with resulting access to the national electricity grid exists. However, the developed power optimization model can be used to suggest power solutions for a base station if the demand and supply characteristics are available.

3. The demonstration of the screening tool with a case study of a remote area in a developing country: the methodology is demonstrated by utilizing a case study of Chittagong and Chittagong Hill Tracts located in the southeastern part of Bangladesh, with representative data sets. In order to implement the developed methodology, existing infrastructures in the area of interest are first reviewed to evaluate the potential of extending the reach of the Internet to last-mile areas. Second, the most cost-effective telecom solutions for providing Internet access are identified in the context of Bangladesh. Criteria for such selection are the cost of ownership per line, bandwidth available, and the level of remoteness from the village to the national Internet backbone. Next, the information on existing infrastructure and technology characteristics are used as inputs to the developed model to generate the Telecom-and-Internet access map for the area of Chittagong and Chittagong Hill Tracts. Finally, various power solutions are suggested for hypothetical high-demand and low-demand telecenters. Due to the unavailability of hourly solar and wind data sets of Bangladesh, the data sets from Virginia Tech Solar Test Facility (VTSTF) are used as a sample. A simulation using a simple dispatch algorithm is performed in order to verify the ability to meet the demand of the designed power system.

1.4 Contributions

The main contributions of this dissertation are: (i) a computer model to produce a Telecom-and-Internet access map that lays the groundwork for providing wide-area Internet access at the least cost; and (ii) a computer model for the design of the least-cost local power supply system to make Internet access possible. These models are then integrated into a methodology useful as a screening tool for policy makers and planners.

Regarding the telecommunication model, the problem is formulated in such a way as to integrate geo-coded (GIS) information and existing infrastructures. This gives the model an ability to

suggest, at the least cost, exact wireless deployment locations, and routes to extend optical fiber to cover a majority of the population. In addition, the problem is optimized based on the percentage of the population covered instead of the areas covered, which makes the model more suitable for planning for the last-mile access.

Regarding the power for the Internet, the development of the model to help in the design of energy systems allows users to select the system that fits their needs and locally available energy resources. The model takes into consideration a comprehensive set of decision criteria that heretofore have not been considered in the literature. These criteria include technical and economic performance of each power generating technology, as well as the trade-off among investment costs, environmental costs, locally available resources and reliability requirements.

Lastly, the case study demonstrates the ability of the model to determine the least-cost telecom and power solutions that can provide Internet access to a remote community. In summary, the uniqueness of this dissertation is that it looks at what is needed to make Internet access possible and sustainable by giving realistic solutions that enable telecom and power infrastructure extension to a remote community. It is believed that by making the two missing elements available to the developing world, it will be possible to establish a mechanism to provide education and new business opportunities through the use of the Internet.

1.5 Organization of Dissertation

This dissertation is divided into three main sections. *Part I is an introduction*, which is composed of Chapters 1 and 2. Chapter 1 is a dissertation introduction. Chapter 2 reviews telecom and power technologies, as well as previous work as described in the literature. *Part II discusses the developed computer models*. This part consists of Chapters 3, 4, and 5. Chapter 3 presents the development of an optimization model to identify opportunity for wide-area Internet access. Chapter 4 describes the development of an optimization model to help in the design of small-scale power supply systems. Chapter 5 presents a simple dispatch algorithm used to measure the performance of the designed power system. *Part III presents a case study*, including Chapters 6, 7, and 8. Chapter 6 provides an update on existing IT infrastructure in Bangladesh, and identifies a network gap in Chittagong and Chittagong Hill Tracts. Chapter 7 discusses the implementation of the telecom model to develop Telecom-and-Internet access maps, and presents telecommunication solutions for the case study of Bangladesh. Chapter 8 implements the use of mixed-integer linear programming for the design of hybrid energy systems, and summarizes power solutions for the assumed high-demand and low-demand telecenter kiosks at various

reliability levels. Lastly, Chapter 9 summarizes major findings and suggests related research activities.

Chapter 2

Literature Review

This chapter consists of four sections. The first section reviews alternate telecommunication technologies for Public Switched Telephone Network (PSTN) access. The second section describes various small-scale distributed generation technologies in terms of their economic and technical performance. The third section presents the work related to the design of a telecommunication infrastructure. Lastly, the fourth section reviews previous work with respect to sizing of hybrid energy systems.

2.1 Telecommunication Systems for PSTN Access

There are various types of access technologies for PSTN access. Typically, technology selection is evaluated based on the remoteness of a village. If the village is within 35 km of the nearest local exchange, Internet access can be provided to that village using one-hop last-mile link, as shown in Fig. 1 (a). However, if the village is further away, i.e. >35 km from the local exchange, at least two transmission hops must be established, as shown in Fig. 1 (b). These two hops are (a) the long-haul signal transmission from the country's telephone exchange to the remote access point and (b) the last-mile transmission from that distribution point to end-users.

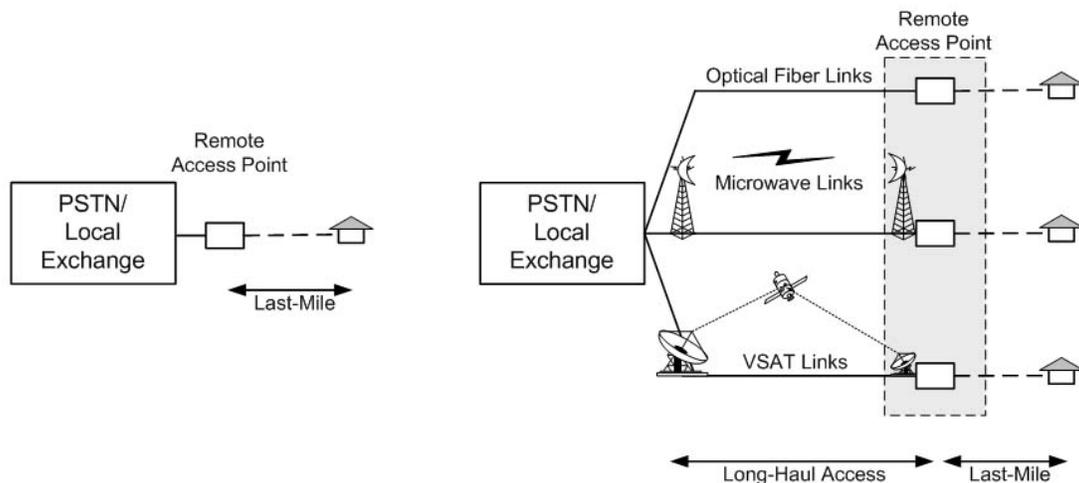


Fig. 1. Technology choices for PSTN access: (a) providing Internet access to an area within 35 km from the PSTN; (b) providing Internet access to an area >35 km from the PSTN

2.1.1 Long-Haul Access Technologies from the PSTN

Generally, there are three transmission alternatives that allow connection from the PSTN to the remote access point. As major cost components to extend the reach of Internet to remote villages, these alternatives are:

A. Optical fiber link: to connect the remote site to the PSTN, optical fiber can be extended along existing transportation infrastructures, i.e. railway and highway networks, to the remote distribution point. Major costs associated with this option include cost of optical fiber cables and costs of labor and installation.

B. Microwave link: another possibility is to use microwave links to connect the remote distribution points to the nation's Internet backbone. Major costs associated with this option include cost of microwave station and spectrum fee. Bandwidth and signal reliability offered by a microwave link are much lower than that offered by optical fiber cable.

C. VSAT link: for the areas with no infrastructure, a satellite dish can be a viable option to remotely communicate to the remote station with the PSTN. In addition to cost of the dish, this option involves leasing bandwidth on the satellite. Major disadvantages of VSAT are that its bandwidth is limited to 2 Mbps.

2.1.2 Last-Mile Access Technologies

This section gives a brief description of technologies capable of providing last-mile Internet access for remote villages. Wireline alternatives include plain old telephone services (POTS), digital subscriber line (DSL), and cable modem. Wireless options include fixed narrowband wireless access systems (wireless in local loop - WLL), fixed broadband wireless access systems (Multipoint Multi-Channel Distribution Systems – MMDS, and Very Small Aperture Terminal - VSAT), wireless local area network (WLAN 802.11), wireless metropolitan area network (WMAN 802.16 and 802.20), and lastly wireless wide area network (WWAN) based on cellular infrastructure.

A. POTS or Plain Old Telephone Services: refer to the standard telephone service that has long been used to provide basic telephony. POTS connect end users to the PSTN through copper wires. To connect to the Internet, a user at home uses a telephone line, with a PC and a modem, to dial an ISP. The data rate provided by standard telephone systems is 56 kbps.

B. DSL or Digital Subscriber Line: is a copper-based broadband technology for the local loop that relies on the telephone network infrastructure to offer high-speed data. Data rates vary with

versions of DSL and loop length. For ADSL, downlink data rate is 6.1 Mbps for the loop length of 3 km, and is 1.5 Mbps for the loop length of 5 km. Uplink data rate is 640 Kbps.

C. Cable Modem: is comparable in performance to the DSL service. It relies on cable TV network that transmits TV and Internet data through coaxial cable. The connection speed will degrade as more users share the same channel, but will not degrade for longer loop length. Typically, downlink speed is 0.5-1 Mbps and uplink speed is 256-500 Kbps.

D. *WLL or CorDECT Wireless Local Loop Systems*: WLL based on Digital European Cordless Telephone (DECT) standard is widely used in several locations in India. The system is composed of a base station, repeater stations and a subscriber unit. The distance between the base station and the subscriber unit is 10 km, which can be extended to 35 km with the use of a repeater station. CorDECT WLL can provide simultaneously telephone and Internet connections. The connection speed is limited to 35-70 Kbps.

E. *MMDS or Multipoint Multi-Channel Distribution Systems*: MMDS is now being used to offer broadband Internet access and voice communication to residential and small business customers in some parts of the United States and Mexico. MMDS offers non line-of-sight (NLOS) plug-and-play broadband wireless access system, which allows users to install subscriber units at home without any visits within 20-km radius. Downlink and uplink speeds can be set according to the vendor, varying from 128 to 256 Kbps, and from 64 to 128 Kbps, respectively.

F. *VSAT or Very Small Aperture Terminal*: VSAT, generally known as satellite technology, can be seen as a viable option in the areas where no wireline is available, or in the areas where the population is so dispersed that the construction of many towers makes other wireless solution expensive. Data rate of a VSAT varies from 64 Kbps to 2 Mbps.

G. *WLAN or Wireless Local Area Network (802.11)*: WLAN technology has been widely deployed with over 1.7 million users worldwide. Currently, WLAN platforms include 802.11a, 802.11b, 802.11g and 802.11n. Maximum possible distance from the access point is roughly 100 meters indoor and 300 meters outdoor. The maximum data rates for 802.11 a, b, g, and n are 54 Mbps, 11 Mbps, 54 Mbps and 320 Mbps, respectively.

H. *WMAN or Wireless Metropolitan Area Network (802.16)*: The 802.16 is the most challenging technology emerging recently for high density metropolitan area network applications. The 802.16 is designed to provide a communication path between a subscriber site and a core network. The superior characteristic of the 802.16 is its ability to provide broadband connection (1.54 Mbps) to 60 customers simultaneously at the distance of up to 50 km from the base station.

At each access point, WLAN technology could be added on to increase mobility to users in the village. The aggregated bandwidth required at the base station to provide 12-24 Mbps to an individual user is 192 Mbps.

I. WMAN or Wireless Metropolitan Area Network (802.20): The 802.20 system is intended to deliver data access to mobile users traveling at the speed of up to 250 km/h. It is expected to boost real-time data transmission rate to 1 Mbps or more with the shorter cell ranges of up to 15 km. Its availability is approximately in 2005 or later.

J. WWAN or Wireless Wide Area Network: WWAN uses cellular networks to enable Internet connection from cell phones. In order to support 2.5G or 3G systems, infrastructure changes, e.g. new base station add-on and software upgrade, will be required on the existing cellular networks, as well as new handsets. The following summarizes the WWAN terminology and its data rate:

GSM: Global System for Mobile Communications (2G)	9.6Kbps
CDMA: Code Division Multiple Access (2G)	14.4Kbps (IS-95A)
GPRS: General Packet Radio Service (2.5G)	171.2Kbps
EDGE: Enhanced Data GSM Environment (2.5G)	384Kbps
CDMA2000: CDMA2000 (3G)	2Mbps
WCDMA: Wideband CDMA (3G)	144kbps in fast moving vehicles

2.2 Distributed Power Generation Technologies

Distributed generation is defined as a small-scale power generating technology located at or near the load. Technologies under consideration include photovoltaic (PV) arrays, wind turbines, engine generators, fuel cells and battery storage. Brief descriptions of each technology are given below.

A. Photovoltaics: PV is a technology that converts sunlight directly into electrical energy. The output is direct current, which can be used directly, converted to alternating current, or stored for later use. PV is the most promising technology to power a small demand in remote area since it requires no fuel. The current PV module price in the U.S. as of July 2004 is \$4.98/watt [8]. Despite its high initial cost, solar electricity can cost less than any other means of producing electricity due to no fuel required, low maintenance needed, long panel life and high reliability. However, PV panels are very difficult to repair if damaged and can be easily stolen.

B. Wind turbines: a wind turbine is a technology that converts the kinetic energy from the wind to mechanical and electrical energy. Since the frequency of the output current from a wind turbine greatly depends on wind speed which is highly variable, the current is usually rectified to give DC output. A single wind turbine can range in size from a few hundred watts (e.g. 300W) for remote applications to more than 5MW for utility applications. Unlike PVs, which have basically the same cost per watt independent of array size, wind turbines get less expensive with increasing system size. At the 50-watt size level, for example, a small wind turbine would cost about \$8/watt compared to \$4.98/watt for a PV module. At 300 watts, on the other hand, the turbine costs are down to \$2.5/watt (\$1.5/watt in the case of the Southwest Windpower Air 403).

C. Engine generators: engine generators, also known as internal combustion (IC) engines, are the most common type of generator used in small and remote power systems throughout the world. They are readily available in most major towns and cities in developing countries. There is usually a well-established spare parts and maintenance network, at both urban and rural centers. Diesel engines usually have a useful lifespan of about 30,000 hours running time, but this can be drastically reduced if maintenance is poor. Efficiency depends on the type of fuel and the loading of the machine. Compared to renewable energy generators, engine generators have much lower capital costs (\$300-600/kW), and produce power on demand. Disadvantages of these generators include fuel dependency, transportation costs, storage costs and emissions.

D. Fuel cells: a fuel cell, an emerging distributed generation technology, is an electrochemical energy conversion device that converts hydrogen and oxygen directly into usable electrical energy without combustion. Fuel cell technologies are of different types depending on their electrolyte. Some of the different electrolyte types include phosphoric acid (PAFC), molten carbonate (MCFC), solid oxide (SOFC) and proton exchange membrane (PEMFC). A number of manufacturers around the world exploit PEMFC technology for residential applications (1kW range). Currently PEMFC prototypes 500W and 1,000W are also available [9]. The current first cost of fuel cells is very high (approximately \$4,000/kW).

E. Batteries: batteries are electrochemical devices that store energy for later used. Batteries must be operated within a certain boundaries to prevent overcharging and undercharging to prolong battery life. The average capital cost of a 12V battery per amp hour from various manufacturers in the U.S. is \$1.70/AH as of July 2004 [10].

2.3 The Design of Telecommunication Infrastructure

The most popular software for the detailed wireless planning is CelPlan [11]. CelPlan offers an integrated wireless planning mostly for cellular technologies. It deals with traffic analysis, RF coverage, link analysis, spectrum management, microwave relocation, and frequency planning.

Other publications related to the design of telecommunication infrastructure try to optimize base station locations alone or with their configurations, e.g. antenna height, tilt and sector orientation, to maximize traffic coverage at a minimum cost. Various optimization methodologies are introduced: the Nelder-Mead simplex method is used by [12]; the simulated annealing optimization technique is used by [13] and [14]; the genetic algorithm is used by [15]; the Tabu Search algorithm is used by [16]; an efficient branch and cut algorithm is introduced by [17] to minimize the number of base stations in a mobile radio network; and neural network is also used for predication of system coverage in [18]. In addition to mobile radio network, base station location optimization for indoor micro-cellular radio environment is also a subject of [19], [20], [21], and [22].

2.4 The Design of Hybrid Energy Systems

There are many software tools that are capable of simulating and determining sizes of equipment in hybrid energy systems. These include HOMER, PVSYST, SOMES, RAPSIM, SOLSIM, INSEL, WATSUN and PV-DesignPro. A brief description of each tool is given below.

A. HOMER: HOMER [23] is a computer model developed by National Renewable Energy Laboratory (NREL) for sizing hybrid energy systems. HOMER models following technologies: PV, wind turbine, run-of-river hydro power, engine generator, utility grid, microturbine, fuel cell, battery bank, and hydrogen storage. HOMER performs simulations for all of the possible system configurations to determine whether a configuration is feasible. Then, HOMER estimates the cost of installing and operating the system, and displays a list of configurations sorted by their life cycle cost.

B. PVSYST: PVSYST [24], developed by Geneva University in Switzerland, is a software package for sizing complete PV systems. It allows determination of PV size and battery capacity, given a user's load profile and the acceptable duration that load cannot be satisfied. The software offers a large database of PV components, meteorological sites, an expert system, and a 3-D tool for near-shading detailed studies.

C. SOMES: SOMES [25] stands for Simulation and Optimization Model for renewable Energy Systems. SOMES is developed at Utrecht University, The Netherlands. Energy technologies

consist of PV, wind turbine, motor generator, electricity grid, battery storage, and several types of converters. The simulation is carried out on an hourly basis. The optimal design is then found by comparing cost of several systems within user-defined boundaries.

D. RAPSIM: RAPSIM [26] or Remote Area Power Supply Simulator, is a computer modeling program developed at the Murdoch University Energy Research Institute, Australia. It is designed to simulate alternative power supply options, including PV, wind turbine, and diesel system. To find optimum solution, users have to change parameters (i.e. increasing the battery size, adding another wind turbine or changing size of diesel generator) and make a judgment of what will be the best suit for their needs. [27] and [28] are examples of using RAPSIM.

E. SOLSIM: SOLSIM [29] is developed at the Fachhochschule Konstanz, Germany. SOLSIM is a simulation tool that enables users to design, analyze, and optimize off-grid, grid-connected and hybrid solar energy systems. Energy sources can be PV, wind turbine, biogas or biomass plant, battery bank and diesel generator. SOLSIM is a software package consisting of different tools: the main simulation program called SOLSIM; the unit to optimize the tilting angle of PV module called SolOpti; the unit to calculate life cycle costs called SolCal; and the unit to simulate wind generators called SolWind.

F. INSEL: INSEL [30] stands for INtegrated Simulation Environment and a graphical programming Language. INSEL, developed by the University of Oldenburg, Germany, is a logistic simulation model for renewable energy systems. It is a block-diagram simulation system where each block represents a system component of predetermined size. Users need to select blocks from the library and interconnect them to define the energy system. [31] presents an application of INSEL.

G. WATSUN-PV: WATSUN-PV [32], developed by the University of Waterloo, Canada, is a comprehensive computer program for the simulation of a large variety of solar energy systems. These include industrial process heating systems, solar PV, diesel hybrid, and PV pumping. The programs use a phenomenological approach to simulate many different solar energy systems. They perform hour-by-hour simulations using actual, typical, or proxy weather data to give long-term performance predictions.

H. PV-DesignPro: PV-DesignPro [33] is used to simulate PV system operation on an hourly basis. It is recommended for systems that have battery storage, which can be stand-alone with generator backup or utility interconnected systems. Users must select a panel type from the data base and

specify the number of parallel connections and series strings. An advantage of PV-DesignPro is that its database already includes most information needed for PV designs.

In addition to the software tools stated above, other methodologies for design of hybrid energy systems are described in various technical publications. These methods, which are described below, include amp-hour (AH) method, knowledge-based approach, simulation approach, trade-off method, probability method, analytical method, linear programming, goal programming, dynamic programming, and non-linear programming.

A. AH method: AH method is the most straightforward method to size PV-battery-diesel hybrid systems. This method is detailed in a handbook of PV design practices by SANDIA [34]. The storage capacity is determined by the number of autonomous days (number of continuous days that the battery can cover the load without sunshine), which is arbitrary selected by the designer (typically 3-7 days). The size of fossil-fuel engine is selected to cover peak demand. This method does not take into account the relationship between the output of PV, generator sets, and storage capacity. Unless the very accurate data is used to select the value for autonomous days, this can easily lead to the specification of oversized components and a suboptimal result. It is used by [35], [36], [37], and [38] to size stand-alone PV systems.

B. Knowledge-based approach: a knowledge-based design approach that minimizes the total capital cost at a pre-selected reliability level is introduced by [39] and [40]. The overall design approach is as follow: first, a year is divided into as many time sections as needed. For each time section, the ratings of energy converters and the sizes of energy storage systems that satisfy the energy needs at the desired reliability level at the minimum capital cost are determined. A search algorithm is used to search for feasible configurations. Since the final design is selected based on the seasonal designs, the users must decide whether to select the worse or the best case designs or the designs in between.

C. Simulation approach: Using a concept similar to HOMER, [41] designs hybrid PV/wind/battery systems using time-step simulation to identify all possible configurations that satisfy the desired level of reliability. An optimal solution is then extracted from these configurations by economic parameters. The reliability index is defined by hours without load supply divided by the total number of hours in the simulation period. This similar approach is also used by [42] to determine optimum configurations. The simulations are done by varying fractions of PV and wind energy from 0 to 1, at the battery-to-load ratio (the number of days that the battery is able to supply the load while fully charged) of 1.25, 1.5, and 2.0, and various energy-to-load ratios (the ratio of the energy produced by renewable components to energy demand).

D. Trade-off method: Trade-off method is introduced by [43] and [44] for multi-objective planning under uncertainty. The idea is intended for use in the design of stand-alone systems with renewable energy sources. This is done by first developing a database that contains all possible combinations of PV plant, wind generator, and battery, given ranges and steps of component sizes. Next, all possible plans are simulated over all possible futures, i.e. $\pm 1\text{m/s}$ variation in the wind velocity, $\pm 10\%$ variation in the global solar insolation. The authors then create a trade-off curve by plotting investment cost and loss of load probability (LOLP) for all possible scenarios, eliminating options with LOLP greater than 10%, and identifying the knee-sets. Robust plans are then identified by the frequency of occurrence of discrete option values in the conditional decision sets. This method yields a small set of robust designs that are expected to work well under most foreseeable conditions. The final decision for the selection of the unique design is left to the decision makers. [45] also uses the similar concepts; however, the trade-off curve is presented in 3-D space of cost of energy ($\$/\text{kWh}$), SO_x emission (kg/year) and expected energy not served (EENS – kWh/year). EENS is a means to measure quality of supply in this paper.

E. Probability method with LPSP: the concept of loss of power supply probability (LPSP) has been introduced by [46] to design stand-alone solar PV systems. This technique enables the determination of the minimum sizes of PV and storage capacity, and yet assures a reliable power supply to the load. The reliability of power supply is measured by the total number of hours per year for which the consumer's power demand is larger than PV supply. The study is performed during a period of one year to collect the state of charge (SOC) of battery as a function of time. The cumulative distribution function of the battery SOC is derived. The LPSP is then determined by calculating the value $[1 - \{\text{cumulative proportion of the time where battery SOC is higher than the SOC min}\}]$. Similar work is done including wind generators in [47]. [48] then adopts this concept to find the optimum size of battery storage coupled with a hybrid PV-wind autonomous system. Long-term data of wind speed and insolation recorded for every hour of the day are deduced to produce the probability density function of combined generation. For the load distribution being considered, the probability density function of the storage is obtained. Finally, the battery size is calculated to give the relevant level of the system reliability using the LPSP technique.

F. Analytical method with LPSP: In [49] and [50], a closed form solution approach to the evaluation of LPSP of stand-alone photovoltaic systems with energy storage, as well as stand-alone wind electric conversion systems, is presented. Similar to [47], the authors define LPSP as the probability of encountering the state of energy stored in battery falling below a certain

minimum value specified. However, instead of using long-term historical data to determine LPSP, the LPSP is determined by integrating the probability density function of power input to the storage. The analytical technique thus involves less data manipulation. Although the LPSP technique is useful and it is proven to work well in hybrid PV/wind/battery systems, this approach can be very complicated when dealing with hybrid energy systems that have other fossil fuel resources. This is due to the fact that this technique requires modeling of probability distribution of those resources. Unlike those for solar and wind energy which can be modeled using Weibull distribution or Beta distribution, the probability density function of fossil fuel resources cannot be modeled since the engine can be controlled manually.

In addition to the above publications, there are several other publications that analyze and estimate reliability of a stand-alone PV system, using loss of load probability (LOLP). These publications include [51], [52], and [53].

G. Linear programming (LP): LP is a well-known tool and has been used in several publications to size hybrid energy systems. [54] gives a very good explanation and insights into how LP can be used to determine PV and wind turbine size in a PV/wind energy hybrid system. The method employs a simple graphical construction to determine the optimum configuration of the two generators that satisfies the energy demand of the user throughout the year. [Note this method excludes battery storage or diesel generators]. LP is also used in [55] to size PV-battery systems, considering reliability of supply. The reliability index used is defined as the ratio of total energy deficit to total energy load. Other LP applications have been shown in [56] and [57].

H. Dynamic programming (DP): [58] describes a computer package ASP (Autonomous System Planning) which determines the optimal expansion plan of an autonomous generation system including diesel units, wind generators and PV generators. This computer model is similar to the WASP expansion planning program for power systems. It integrates simulation technique as well as dynamic programming to obtain the optimal design. Since it is primarily used for utility-scale applications, it does not integrate the use of battery storage, which is the most important equipment in remote applications.

I. Non-linear optimization: In [59] and [60], non-linear programming has been developed. This approach aims to take the interdependency between sizing and system operation strategy into account. Thus, it can simultaneously determine optimal sizing and operation control for hybrid energy systems.

2.5 Conclusions

This chapter summarizes various telecommunication and power access options, and also reviews previous work with respect to the design of telecommunication and small-scale energy systems. With respect to the design of telecommunication systems, this work is not intended to perform a very detail analysis like CelPlan or other publications in the field. Alternatively, it aims at performing a rough analysis to produce Telecom-and-Internet access maps, based on available existing infrastructures. This is in order to suggest both optimum locations for wireless deployment (as last-mile access points) and route to extend optical fiber (as Internet backbone) to provide Internet access to a majority of the population in the selected area at the least possible cost. In addition, unlike most publications, the model is designed to maximize population coverage, which is much more important than maximizing coverage areas. With respect to the design of small-scale energy systems, several previous works have certain limitations: some give oversized components; some leave many design configurations for users to select; and some are very lengthy and time consuming. This work produces a framework for the design of stand-alone hybrid energy systems that takes into account a complete set of decisions, which have not been considered in the literature. The result is one power supply configuration that best optimizes various decision sets.

PART II: METHODOLOGY

Chapter 3

Telecommunication Model

Having identified the problem and technologies that can bridge the digital divide, this chapter presents a framework to develop a Telecom-and-Internet access map for an area of interest. The Telecom-and-Internet access map suggests how to provide wide-area Internet access at the lowest initial cost. To begin with, key concepts and assumptions are discussed in section 3.1. Then, section 3.2 describes the structure of the model. Lastly, section 3.3 details the formulation of the optimization problem, including the objective function and constraints.

3.1 Model Concept and Key Assumptions

Given a set of geo-coded inputs about existing infrastructures in an area of interest, the model selects potential locations for the deployment of wireless base stations, and routes to extend optical fiber from the national PSTN to selected new base stations. The goal is to produce a Telecom-and-Internet access map that suggests how to provide Internet access for a specified fraction of the total population in the selected area at the least possible cost.

The following descriptions list key assumptions of the model:

- Wireless technology to provide Internet access to a remote area is preselected by users. This selection should be based on the cost per line or the cost of ownership per bandwidth available at the base station. Any technology can be selected as the model only requires its investment cost and coverage radius as inputs.
- In order to determine the total population served, it is assumed that the wireless coverage is a perfect circle; terrain characteristics are therefore discarded. This assumption is valid because the distribution of population is integrated into the model based on GIS population maps. In addition, it is assumed that Internet access is provided in a form of a village center or a kiosk. As long as the kiosk is in the location that can send and receive the signal, people within a certain distance from the kiosk can have access to the Internet at the kiosk.
- A set of potential base station locations are chosen by the model, and are distributed along railway tracks and highway routes. It is important that new base stations be set up

on these routes for easy accessibility. An additional set of potential base station locations can also be arbitrary entered by users.

- In order to connect each base station to the national PSTN, optical fiber should be extended to each potential location from the national PSTN. Optical fiber is selected for long-haul transmission because it is able to support high bandwidth ($>Gbps$), and provide more reliable connections than microwave links or VSAT. In addition, laying optical fiber is much more cost-effective as opposed to a VSAT option in the long run (Chapter 7 validates this statement in the context of Bangladesh).
- Existing transportation infrastructures, i.e. railway and highway networks, are used as the right-of-way for optical fiber extension. The advantages of laying cable alongside these infrastructures are that railway tracks and national highway routes reach a majority of the population; in addition, most railways and highways possess a structure where optical fiber can be easily laid at low cost.
- The locations of the national PSTN are entered by the user, based on the country profile.

3.2 Structure of Telecommunication Model

The telecommunication model is formulated as the combination of a set-covering problem and a network flow problem. The former is used to determine potential wireless base station locations to cover a given percent of the total population in the region of interest. The latter is used to determine the least-cost path to extend optical fiber along transportation infrastructures from source nodes to destination nodes. Source nodes are defined as the nodes from which optical fiber can be extended. These source nodes must be located at the national PSTN. Destination nodes are defined as the nodes to which optical fiber must be extended. These destination nodes are potential base station locations. A set of nodes, and arcs connecting nodes, is constructed based on the information of railway and highway networks, since it is assumed that optical fiber must be laid along side existing transportation infrastructures. Fig. 2 presents the structure of this model.

A. User inputs: the following inputs are required to run the model: the goal or the percentage of population to be served (χ); technology information, i.e. coverage distance (r), and one time costs (α_i); GIS data of source nodes and destination nodes in latitude and longitude; and other economic parameters, including costs of extending optical fiber cable along railway and highway networks (δ_{ij}).

B. GIS data sets in e00 format: the following data sets are required in e00 format: the country political boundary, population density, and national railway and highway networks. The political boundary data is used to generate a country map and to allow a user to select the area of interest. The area of interest is captured in a matrix, size c by d , that contains 0 or 1. The element 0 in the matrix represents unselected areas, whereas the element 1 in the matrix represents selected areas. The parameters c and d represent the distance (in km) from north to south and from east to west of the selected area, respectively. Then, the above 0-1 matrix is logically multiplied (AND) with the population density data to produce the number of population in the area of interest, which is the matrix $[P_{cd}]$. Lastly, transportation networks are used to generate nodes, arcs, and length of arcs for the network flow problem. They are also used to generate potential locations of wireless base stations since it is assumed that potential base station locations must be distributed along railways and highways.

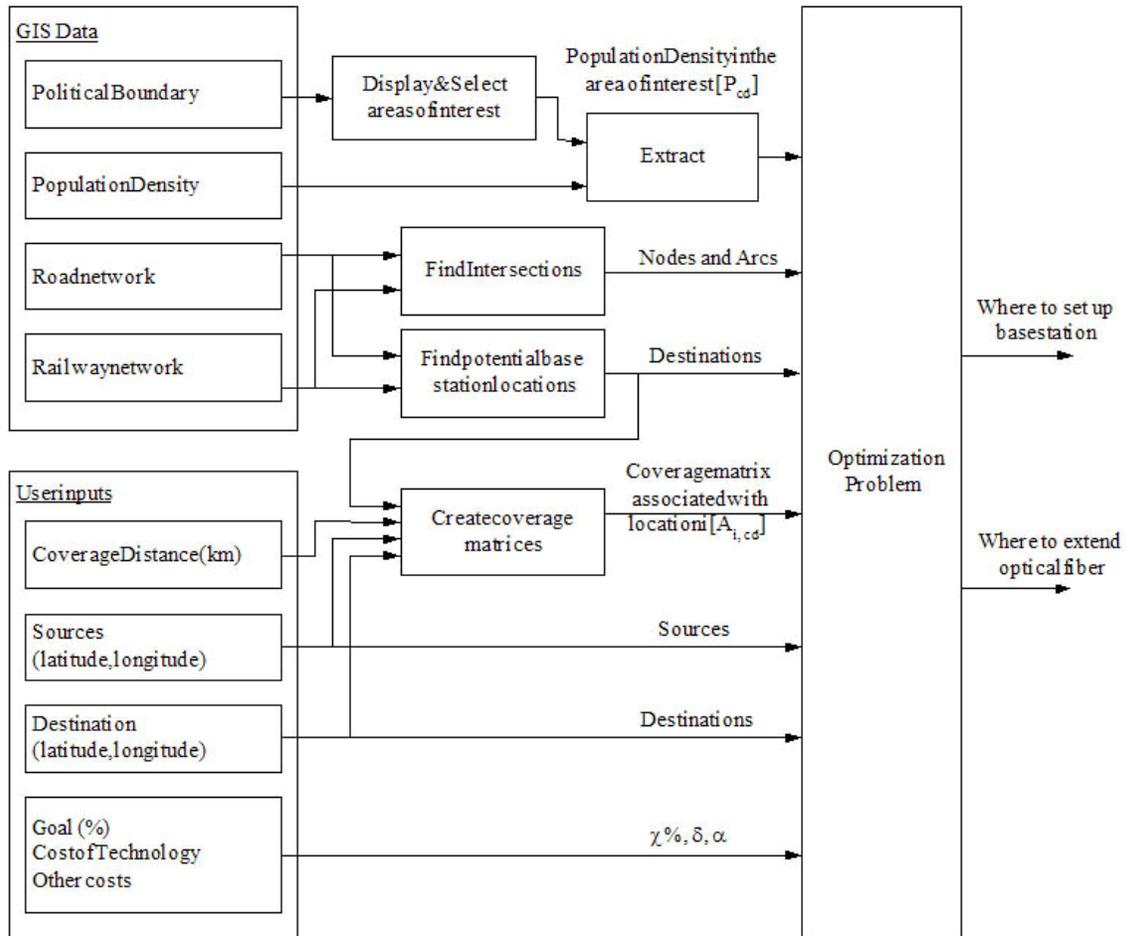


Fig. 2. Telecommunication optimization model

C. *Construction of railway and highway networks*: using the given GIS data of railway and highway networks, arc ID, tail ID, latitudes and longitudes of tail nodes, head ID, and latitudes and longitudes of head nodes are extracted. Then, intersections between every railway route and every highway route must be calculated in order to generate a new network that combines railway network, highway network, and their intersections. To determine the intersections of railway and highway networks, firstly, one arc of the railway network is selected. Then, the program checks for intersections of that arc with each and every arc of the highway network. This process is repeated until all railway and highway arcs are considered. This calculation is possible because, in fact, the GIS data available represents a network using several interconnected straight lines.

In general, the intersection of any two arcs can be calculated as follow: as shown in Fig. 3, assuming that the arc UV intersects the arc PQ at point A.

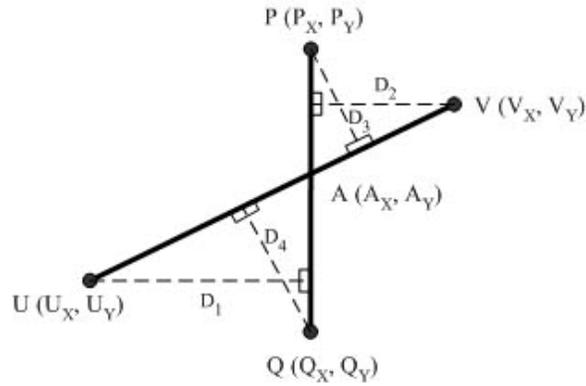


Fig. 3. The arc UV intersects the arc PQ at point A

Step 1: calculate the distances D_1 and D_2 , which are defined as perpendicular distances from points U and V, respectively, to the arc PQ, using the following formulas.

$$D_1 = \frac{|a \cdot U_x + b \cdot U_y + c|}{\sqrt{a^2 + b^2}} \quad (\text{eq. 3-1})$$

$$D_2 = \frac{|a \cdot V_x + b \cdot V_y + c|}{\sqrt{a^2 + b^2}} \quad (\text{eq. 3-2})$$

where $a = Q_y - P_y$; $b = P_x - Q_x$; and $c = Q_x P_y - P_x Q_y$

Step 2: similarly, calculate the distances D_3 and D_4 , which are defined as perpendicular distances from points P and Q, respectively, to the arc UV.

$$D_3 = \frac{|a \cdot P_X + b \cdot P_Y + c|}{\sqrt{a^2 + b^2}} \quad (\text{eq. 3-3})$$

$$D_4 = \frac{|a \cdot Q_X + b \cdot Q_Y + c|}{\sqrt{a^2 + b^2}} \quad (\text{eq. 3-4})$$

where $a = V_Y - U_Y$; $b = U_X - V_X$; and $c = V_X U_Y - U_X V_Y$

Step 3: calculate the intersection point from the point of view of the arc UV and the arc PQ, based on the following equations:

From the point of view of the arc UV, the intersection A (A_x, A_y) is calculated as:

$$A_X = \frac{D_2}{D_1 + D_2} \cdot U_X + \frac{D_1}{D_1 + D_2} \cdot V_X \quad \text{and} \quad A_Y = \frac{D_2}{D_1 + D_2} \cdot U_Y + \frac{D_1}{D_1 + D_2} \cdot V_Y \quad (\text{eq. 3-5})$$

From the point of view of the arc PQ, the intersection A (A_x, A_y) is calculated as:

$$A_X = \frac{D_4}{D_3 + D_4} \cdot P_X + \frac{D_3}{D_3 + D_4} \cdot Q_X \quad \text{and} \quad A_Y = \frac{D_4}{D_3 + D_4} \cdot P_Y + \frac{D_3}{D_3 + D_4} \cdot Q_Y \quad (\text{eq. 3-6})$$

Step 4: compare the values of A_x and A_y from eq. 3-5 and 3-6. The two arcs intersect if and only if the values of A_x and A_y from eq. 3-5 and those from eq. 3-6 are the same.

After having calculated all the intersection points of railway and highway networks, the new network is constructed by collecting all node IDs, latitudes and longitudes from railway network, highway network, and the intersection points. Note that one intersection generates four arcs, which are arcs UA, VA, PA, and QA. The length of each arc must also be collected. The length of an arc that connects the head node (U_X, U_Y) to the tail node (A_X, A_Y), for example, is calculated using the equation below. The typical value to convert the degree of latitude and longitude to the distance in km is 111.2 km/degree.

$$\text{length} = \text{km_deg} \times \sqrt{(U_X - A_X)^2 + (U_Y - A_Y)^2} \quad (\text{eq. 3-7})$$

The cost of each arc (δ_{ij}) is then calculated by multiplying the length of the arc (km) by the cost to lay fiber on that arc (\$/km), which is either the cost to lay fiber on railway line or the cost to lay fiber on highway routes.

D. Selection of potential base station locations: the only requirement to select potential base station locations is that those locations must be located on the railway or highway networks for easy accessibility. Thus, the model extracts the locations of head nodes and tail nodes of each railway and highway arcs, and uses them as potential base station locations. As mentioned earlier, an additional set of potential locations can be manually inputted, as well as an unnecessary set of pre-inputted locations can be removed.

E. Creation of coverage matrices: once the source and destination nodes are determined, the model uses this information and the coverage distance of the pre-selected wireless technology to generate the coverage matrix $[A_{i,cd}]$, size c by d , associated with each base station destination i . The value of the element $A_{i,cd}$ in the coverage matrix $[A_{i,cd}]$ depends on the base station location and the coverage radius of the selected wireless technology. The element $A_{i,cd}$ is 1, when any location (c, d) is in the coverage area of a base station $i (X_i, Y_i)$. The element $A_{i,cd}$ is 0, when any location (c, d) is outside the coverage area of a base station $i (X_i, Y_i)$. Since it is assumed that the wireless coverage is a perfect circle, the relationship between the element $A_{i,cd}$ and the location (c, d) are shown mathematically in eq. 3-8 and eq. 3-9, respectively, where r is the coverage radius of the selected wireless technology.

$$A_{i,cd} \text{ is 1, when } (X_i - c)^2 + (Y_i - d)^2 \leq r^2 \quad (\text{eq. 3-8})$$

$$A_{i,cd} \text{ is 0, when } (X_i - c)^2 + (Y_i - d)^2 \geq r^2 \quad (\text{eq. 3-9})$$

All data sets, i.e. χ , r , α_i , δ_{ij} , $[P_{cd}]$, $[A_{i,cd}]$, are then used as inputs to the optimization problem. It is important to mention that preprocessing of the coverage matrix $[A_{i,cd}]$ to integrate a complex terrain information is possible. However, this is out of the scope of this study.

3.3 Formulation of the Optimization Model

The overall objective function is to minimize the total installation costs, which are (i) the cost of base station installation to cover χ percent of population (the set-covering problem), and (ii) the cost of optical fiber extension along transportation infrastructures (the network flow problem). The mix-integer linear programming formulation of this problem, which is written in C++ with CPLEX as an optimizer, is as shown below:

$$\min \sum_{i=1}^n \alpha_i \cdot X_i + \sum_{i=1}^n \sum_{j=1}^n \delta_{ij} \cdot Y_{ij} \quad (\text{eq.3-10})$$

where

- X_i : Integer decision variable – a decision to install wireless technology at node i .
- α_i : Costs of wireless base stations installed at node i ; these costs are the cost of base station and the cost of tower.
- Y_{ij} : Integer decision variable – a decision to lay fiber along arc ij .
- δ_{ij} : Costs of optical fiber extension along arc ij .
- n : Total number of nodes in the network.

Subject to:

A. Upper bound and lower bound constraints: for decision variables X_i and Y_{ij} , both decision variables are of integer type. Thus, X_i and Y_{ij} are either 0 or 1.

$$X_i \in \{0, 1\} \text{ and } Y_{ij} \in \{0, 1\} \quad (\text{eq. 3-11})$$

B. Number of population served: summation of the total population served ($\sum \sum P_{cd} E_{cd}$) must be greater than χ percent of the total population in the area of interest.

$$\sum_{d=1}^D \sum_{c=1}^C \{P_{cd} \cdot E_{cd}\} \geq \chi \cdot \sum_{d=1}^D \sum_{c=1}^C P_{cd} \quad (\text{eq. 3-12})$$

Where

- P_{cd} : Population associated with an area (c, d) , see Fig. 4(a).
- E_{cd} : Integer decision variable: $E_{cd} = 1$ if an area (c, d) is covered by at least one selected base station; $E_{cd} = 0$ otherwise. See Fig. 4(b).

Since E_{cd} is a integer decision variable, the following constraint defines the upper bound and lower bound constraints for E_{cd} .

$$E_{cd} \in \{0, 1\} \quad (\text{eq. 3-13})$$

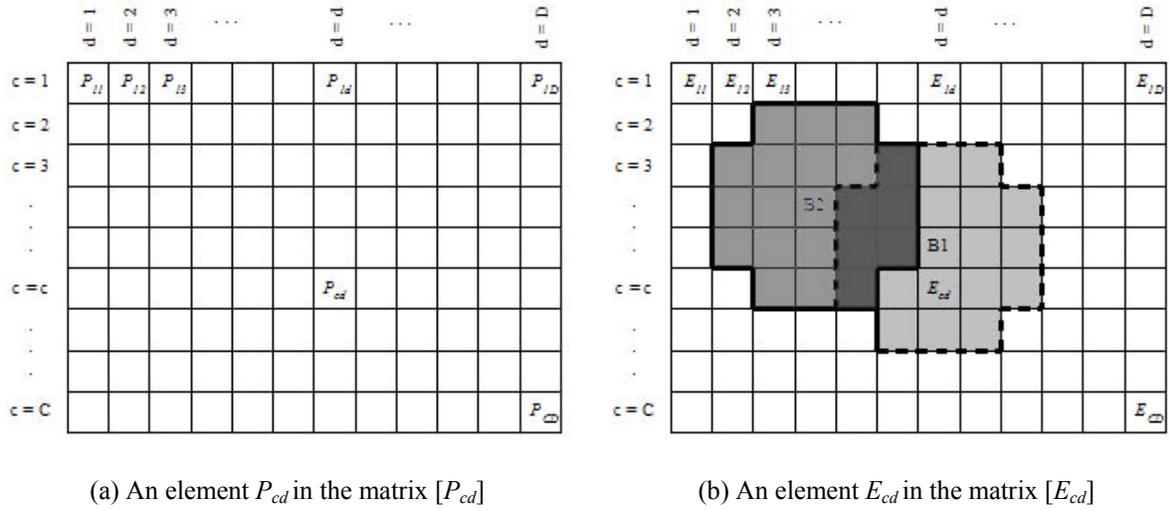


Fig. 4. (a) An element P_{cd} ; and (b) an element E_{cd} ; B1 and B2 are base station locations, and the areas in gray are their coverage areas. The values of E_{cd} in the white area are 0; and those in the gray areas are 1.

C. Constraints associated with E_{cd} : in order for the model to know that E_{cd} is 1 if an area (c, d) is covered by at least one selected base station, and that E_{cd} is 0 if an area (c, d) is not covered by any one base station, the following constraints are needed.

$$\text{For all } c \text{ and all } d, \quad \sum_{i=1}^n A_{i,cd} \cdot X_i \leq M \cdot E_{cd} \quad (\text{eq. 3-14})$$

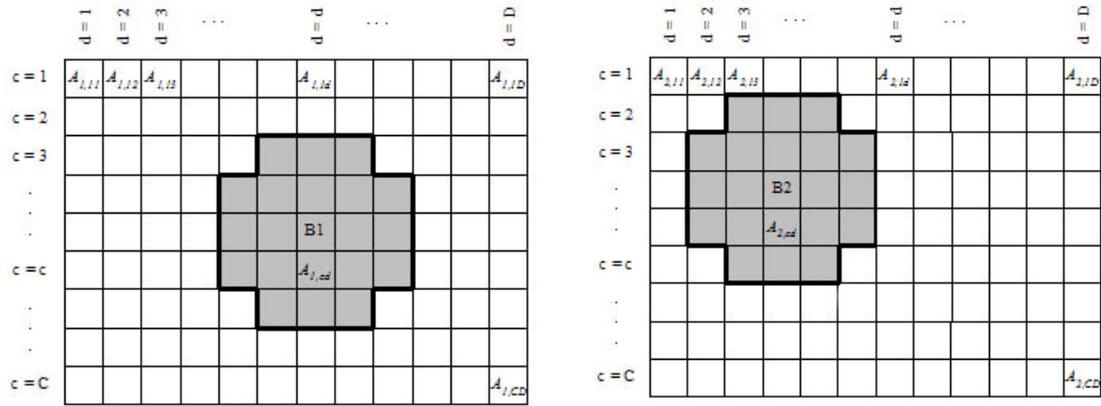
$$\sum_{i=1}^n A_{i,cd} \cdot X_i \geq E_{cd} \quad (\text{eq. 3-15})$$

where

$A_{i,cd}$: An element in the coverage matrix $[A_{i,cd}]$ associated with each base station i : if an area (c, d) is covered by the base station i , $A_{i,cd} = 1$; if an area (c, d) is not covered by the base station i , $A_{i,cd} = 0$, see Fig. 5.

M : Any large number.

The above equations imply that, considering any area (c, d) , if that area is covered by at least one base station (both $A_{i,cd}$ and X_i are 1 for at least one i), E_{cd} will be forced to 1; if that area is not covered at all by at least one base station (both $A_{i,cd}$ and X_i must be 0 for all i), E_{cd} will be forced to 0. Fig. 5(a) and (b) illustrate the value of $A_{i,xy}$, as an example, for the base station i , where i represents base stations B1 and B2, respectively.



(a) An element $A_{1, cd}$ in the coverage matrix $[A_{1, cd}]$ for the base station B1 (b) An element $A_{2, cd}$ in the coverage matrix $[A_{2, cd}]$ for the base station B2

Fig. 5. (a) An element $A_{1, cd}$ for base station B1; (b) an element $A_{2, cd}$ for the base station B2. $A_{i, xy}$ is 1 when the location (x, y) is in the coverage area of a base station i (the gray area); $A_{i, xy}$ is 0 when the location (x, y) is not in the coverage area of a base station i (the white area).

D. Constraints related to the network flow problem: with respect to the network flow problem, a connected network is constructed from the GIS data sets of railway and highway networks. Fig. 6 gives an example of a connected network of six nodes that include one source node, one destination node, and four transshipment nodes.

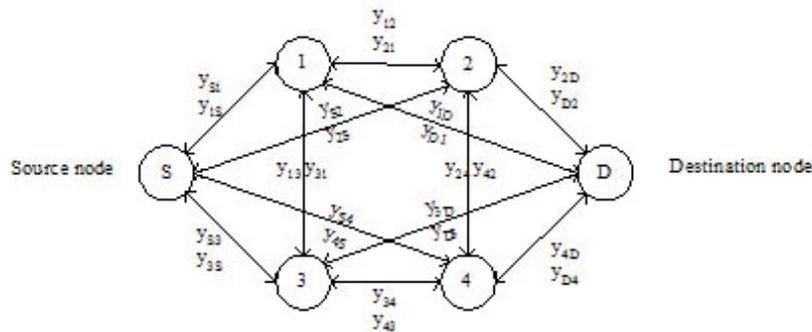


Fig. 6. A network with one source node, one destination node, and four transshipment nodes

Where y_{ij} is a flow through arc $i \rightarrow j$, or a decision to lay fiber from node i to node j . And, the given information is u_{ij} , which is an arc capacity for arc $i \rightarrow j$. The value of u_{ij} equals the number of destination nodes, in this problem. This implies that, for all arcs ij , $0 \leq y_{ij} \leq u_{ij}$.

Thus, for each node i ,

$$\sum_{j=1}^n y_{ij} - \sum_{j=1}^n y_{ji} = b_i \quad (\text{eq. 3-16})$$

The first summation in the node constraints represents the total flow out of node i , whereas the second summation represents the total flow into node i , so the difference is the net flow generated at this node, which is b_i . The value of b_i depends on the nature of node i , $b_i > 0$ if node i is a source node; $b_i < 0$ if node i is a destination node; and $b_i = 0$ if node i is a transshipment node.

A necessary condition to this problem is that:

$$\sum_{i=1}^n b_i = 0 \quad (\text{eq. 3-17})$$

That is, the total flow being generated at the source nodes equals the total flow being absorbed at the destination nodes. Finally, the decision variable y_{ij} is related to the integer decision variable Y_{ij} in the objective function as shown below:

$$y_{ij} + y_{ji} \leq M \cdot Y_{ij} \quad (\text{eq. 3-18})$$

$$y_{ij} + y_{ji} \geq Y_{ij} \quad (\text{eq. 3-19})$$

That is, for each arc ij , if there is a flow either from node i to node j or from node j to node i , Y_{ij} are forced to 1. If there is no flow through arc ij , Y_{ij} are forced to 0.

3.4 Conclusions

This chapter presents the model to produce a Telecom-and-Internet access map. This model serves as a tool to produce the Telecom-and-Internet access map of a region or a small country. The map suggests potential areas to set up new wireless base stations so a majority of the population can be served at the least cost. The ‘costs’ in this study include the one-time costs of base stations, towers, as well as the one-time costs of optical fiber extension to each base station from the national PSTN. The latter should be taken into account because optical fiber cables can provide higher bandwidth and more reliable connections than microwave links and VSAT. In addition, optical fiber option is much more cost-effective as compared to the VSAT option in the long run. Once the Telecom-and-Internet access map is generated, site surveys must be conducted to determine actual site locations and actual tower height, so the actual investment costs can be obtained.

Chapter 4

Hybrid Energy System Model

The purpose of this chapter is to create a framework to model a stand-alone hybrid energy system that accommodates a more comprehensive set of decisions. Section 4.1 describes the structure of the power optimization model. Section 4.2 presents a hybrid energy system configuration and illustrates how the various components interact. Section 4.3 describes the mathematical model of each technology. Then, section 4.4 presents the objective function of the optimization problem and the associated constraints. The last section describes the limitation of the model and the additional data needed for a specific location.

4.1 Structure of the Power Model

The power optimization model is formulated as mix-integer linear programming. The output of this model is the optimal configuration of a hybrid energy system that takes into account technical performance of supply options, the 20-year life cycle cost (LCC) of equipment, locally available energy resources, demand characteristics, environmental costs, and system reliability. Small-scale power generating technologies under consideration include solar photovoltaics (PV), wind turbines (WT), internal combustion (IC) engines, proton exchange membrane (PEM) fuel cells, and battery storage. This research concentrates on PEM fuel cells that use the hydrogen derived from natural gas. The rationale to justify the use of these PEM fuel cells is presented in Appendix A. The structure of this model is presented in Fig. 7.

The following inputs are required to run the model:

- *Hourly demand characteristics*: these characteristics can be given either for each day, from Monday to Sunday, or for weekdays and weekends.
- *Locally available energy resources*: these include hourly solar insolation data (W/m^2), hourly wind speed (m/s), as well as cost of fossil fuels in the village (\$/liter or \$/MMBTU).
- *Technical and economic performance of supply options*: these characteristics include, for example, rated power for PV, power curve for WT, fuel consumption characteristics for IC engines and PEM fuel cells, and minimum and maximum state of charge (SOC) of a battery bank.

- *Externality costs and emission factors*: externality costs must be given in \$/lb for all emissions; emission factors must be given in lb/kWh for IC engines and PEM fuel cells.
- *Reliability requirement*: this parameter must be given in terms of reliability requirement, i.e. 100%, 90% or 80%.

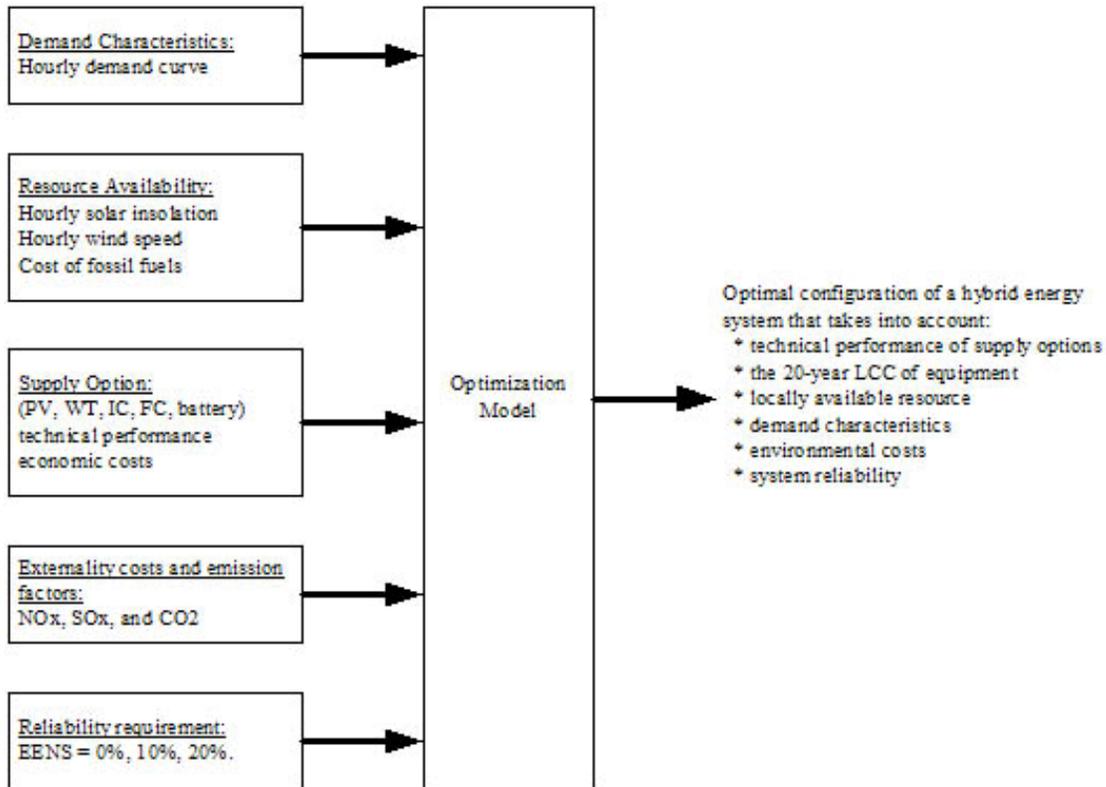


Fig. 7. Power Optimization Model

4.2 Hybrid Energy System Configuration

Embedded power generation is defined as the interconnection of several distributed generators (PV, WT, IC engines and PEM fuel cells) and a set of batteries. In this study, a hybrid energy system is based on a generalized three-bus configuration, as shown in Fig. 8.

The three buses are a DC bus, an AC bus, and a load bus. Technologies that generate DC current – PV, battery, WT, and PEM fuel cells – are connected to the DC bus. Technologies that generate AC current, i.e. IC engines, are connected to the AC bus. It is assumed that only AC appliances are used and are connected to the load bus. This is because AC appliances are compatible with grid electricity, and are useful when the grid is extended to a village. An inverter, or a DC-to-AC converter, is used to convert DC current to AC current (from the DC bus to serve the AC load).

The energy from all generating units (PV, WT, IC engines and PEM fuel cells) is allowed to charge battery banks. An AC-to-DC converter is used to convert AC current from IC engines to DC current to charge the battery. A charge controller is used to control the charge and discharge current from the battery. To serve the load, electrical energy can be produced either directly from PV, WT, IC engines, PEM fuel cells, or indirectly from the battery. It is assumed that diesel oil is a fuel input to an IC engine, whereas natural gas is a fuel input to a fuel processor to produce hydrogen for PEM fuel cells. The use of IC engines or PEM fuel cells with other fuel types can be modeled by changing system parameters to reflect the change in fuel consumption characteristics (e.g. fuel heating values, and efficiency of the engines).

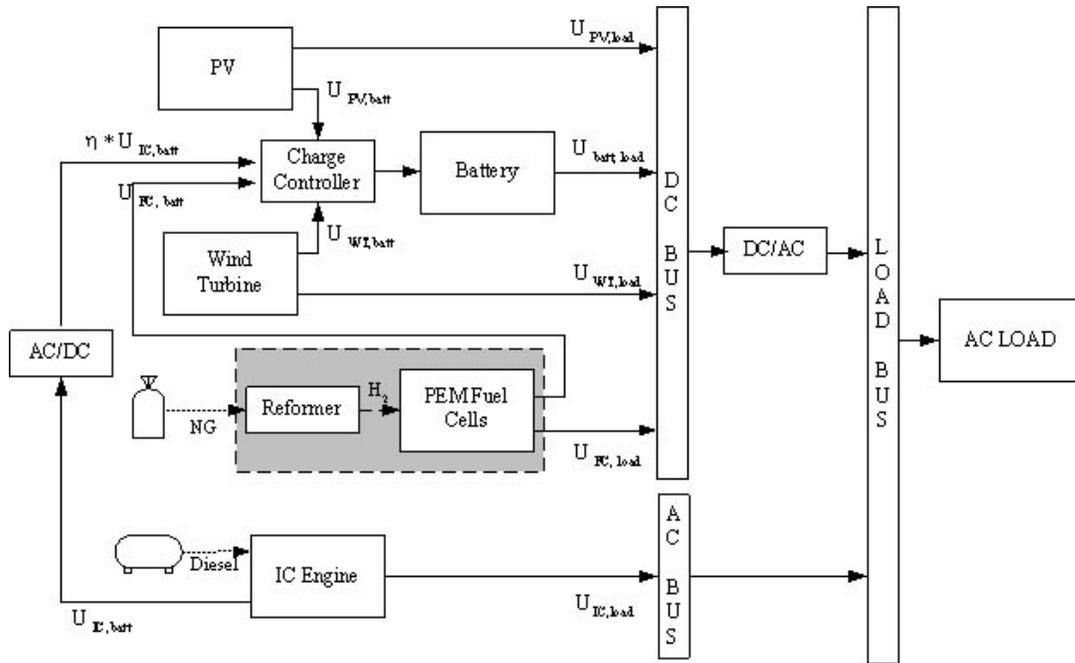


Fig. 8. The configuration of a hybrid energy system

As shown in Fig. 8, the energy generated from all generating technologies can be directed to serve the load and charge the battery. These relationships are expressed in eq. 4-1 through eq. 4-4, for PV, WT, IC engines and PEM fuel cells, respectively.

$$U_{PV} = U_{PV,load} + U_{PV,batt} \quad (\text{eq. 4-1})$$

$$U_{WT} = U_{WT,load} + U_{WT,batt} \quad (\text{eq. 4-2})$$

$$U_{IC} = U_{IC,load} + U_{IC,batt} \quad (\text{eq. 4-3})$$

$$U_{FC} = U_{FC,load} + U_{FC,batt} \quad (\text{eq. 4-4})$$

In any hour i , the energy available to charge the battery is shown in eq. 4-5, and the energy available from the battery to serve the load is shown in eq. 4-6.

$$U_{batt,in} = U_{PV,batt} + U_{WT,batt} + U_{FC,batt} + \eta_{inv} \times U_{IC,batt} \quad (\text{eq. 4-5})$$

$$U_{batt,load} = \eta_{batt} \times (U_{PV,batt} + U_{WT,batt} + U_{FC,batt} + \eta_{inv} \times U_{IC,batt}) \quad (\text{eq. 4-6})$$

Finally, the total energy available to serve the load is written in eq. 4-7.

$$U_{load} = \eta_{inv} \times (U_{PV,load} + U_{batt,load} + U_{WT,load} + U_{FC,load}) + U_{IC,load} \quad (\text{eq. 4-7})$$

where

- U_x : Energy output from technology x (kW in one hour).
- $U_{x,load}$: Energy output from technology x directed to the load.
- $U_{x,batt}$: Energy output from technology x directed to the battery.
- x : x stands for PV, WT, IC or FC.
- $U_{batt, in}$: Energy input to the battery.
- $U_{batt, load}$: Energy generated from the battery to the load that takes into consideration round-trip efficiency of the battery.
- η_{inv} : Efficiency of AC-to-DC or DC-to-AC inverters.
- η_{batt} : Round-trip efficiency of the battery.

4.3 System Component and Modeling

A. Solar Cells: In order to represent PV characteristics in operating conditions that differ from the standard test condition (1000 W/m², 25°C cell temperature), the influences of solar irradiation and ambient temperature on PV characteristics are modeled. The influence of solar intensity is modeled by considering that power output of the PV module is proportional to the irradiance [61]. On the other hand, the temperature effect is represented by a temperature coefficient of power (%/C°). Finally, inverter efficiency is multiplied by the DC output to convert DC output to AC output, as shown in eq. 4-8.

$$U_{jysi} = P_{j=PV} \times \eta_{inv} \times \left(\frac{E_{ysi}}{E_0} \right) \times \left(1 - T_c \cdot (T_{ysi} - 25^\circ) \right) \quad (\text{eq. 4-8})$$

In eq. 4-8, $U_{jysi, j=PV}$ is the energy output from the PV system in year y , season s , and hour i ; $P_{j=PV}$ is the rated power of PV panels in hour i ; η_{inv} is the inverter efficiency; E_{ysi} is the solar irradiation in year y , season s , and hour i ; E_0 is the solar irradiation at the standard condition; T_c is a temperature coefficient; and T is the ambient temperature in $^{\circ}\text{C}$.

B. Wind turbines: To model the performance of a wind turbine, the power curve of the wind turbine must be obtained in order to find mathematical equations representing the power curve. As an example, Fig. 9 shows the actual AIR403 power curve obtained from the owner's manual, and the modeled power curve determined, according to eq. 4-9 ($a = 3.2009$; $b = -6.8011$; $c = -14.474$; and WS_{ysi} = wind speed in hour i , season s , year y).

$$U_{jysi, j=WT} = \begin{cases} 0 & ; WS_{ysi} < 3.5 \\ a \times WS_{ysi}^2 + b \times WS_{ysi} + c & ; 3.5 \leq WS_{ysi} < 17.5 \\ a \times WS_{ysi}^2 + b \times WS_{ysi} + c \Big|_{WS_{ysi}=17.5} & ; 17.5 \leq WS_{ysi} < 18 \\ 130 & ; WS_{ysi} > 18 \end{cases} \quad (\text{eq. 4-9})$$

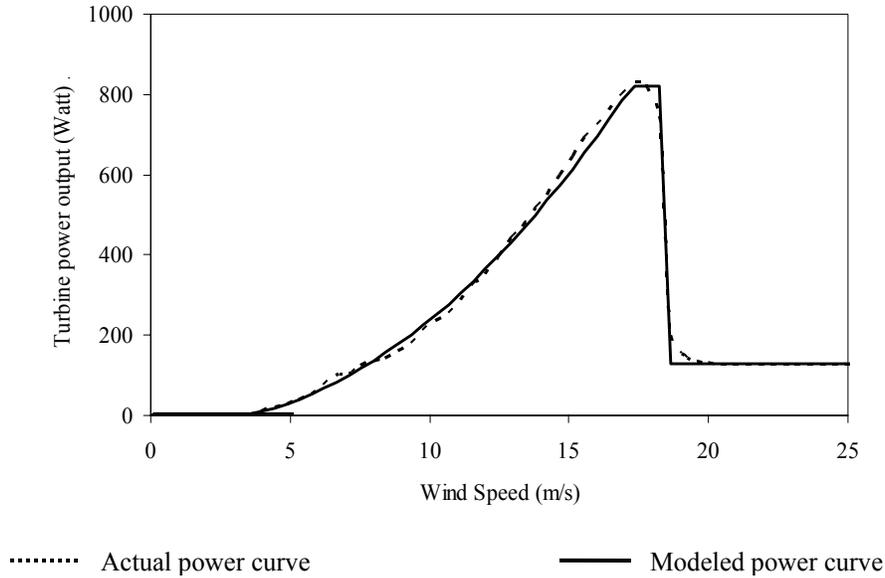


Fig. 9. An actual power curve of AIR403 from the manufacturer [62] and the modeled power curve

It should be noted that a typical wind turbine does not generate power after its cut-off speed; however, the AIR403 model uses a unique rotor blade that twists the blade and stalls the rotor as the cut-off speed is reached. According to the data from the manufacturer, the turbine output is roughly 130 watts if wind speed is greater than approximately 18 m/s.

C. IC engines: Generally, a diesel fuel consumption characteristic of an IC engine is a linear function of its electrical power output [63], as shown in eq. 4-10. The F_0 and F_1 are the parameters that required as inputs to the model.

$$F = F_0 + F_1 \times U_{IC} \quad (\text{eq. 4-10})$$

where

F : Diesel fuel consumption rate (liter/h).

F_0 : Diesel fuel consumption rate at no load (liter/kW/h).

F_1 : Incremental diesel fuel consumption rate (liter/kWh).

U_{IC} : Hourly energy generation from an IC engine (kWh).

Typically, the constants F_0 and F_1 are given by a manufacturer. For example, diesel fuel consumption data of a 6-kW diesel generator set (Cummins Power) model DNAC 50 Hz [64] is available in l/h at $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$ and full loads. This fuel consumption data is plotted against the engine power output per kW, as shown in Fig. 10 (in l/h per kW) with its linear curve fitting.

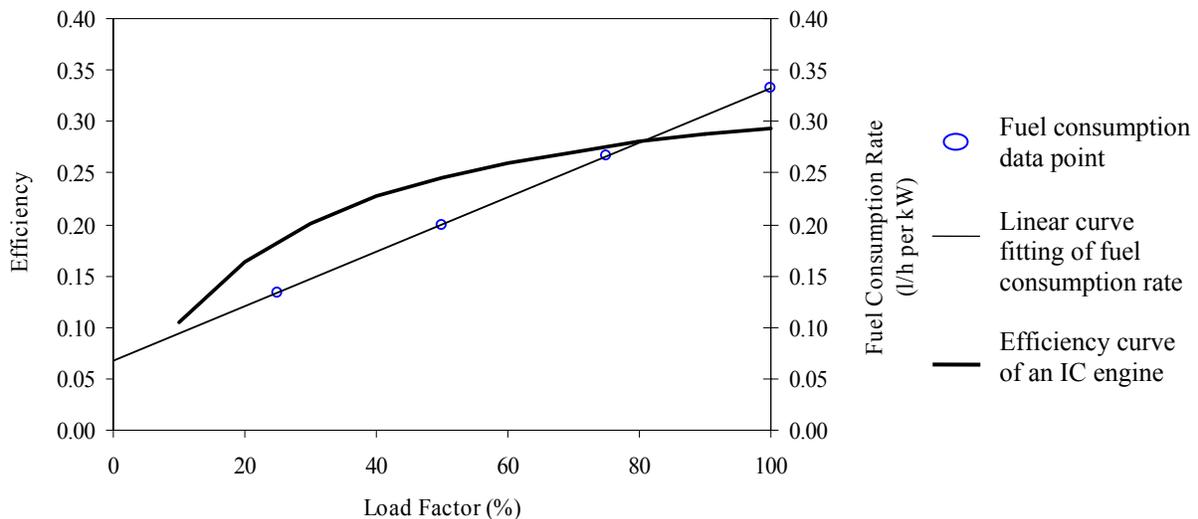


Fig. 10. Efficiency and fuel consumption characteristics of IC engines based on DNAC 50Hz

Fig. 10 also shows efficiency of IC engines at various load levels. The efficiency at a specific load factor is determined by dividing the total energy output from the IC engines (in BTU/h) by the energy content of the total amount of diesel fuel input (in BTU/h). For example at the rated load or 1 kW, total fuel consumption is 0.3333 l/h per kW (1 liter = 34,475 BTU). Thus, the

efficiency of an IC engine at full load in one hour is calculated as $1 \text{ kW} (3,413 \text{ BTU})/0.3333 \text{ liter} (11,492 \text{ BTU}) = 0.297$. This is equivalent to an overall efficiency of 29.7%.

As seen in Fig. 10, the efficiency of an IC engine is higher at the higher loading rate, and is lower at the lower loading rate. Typically, low-load operation leads to higher fuel consumption, higher maintenance costs and an increase in wear and tear. This research assumes that minimum generation of an IC engine is at 30 percent load factor, as recommended by [65].

D. PEM fuel cells: To model the technical performance of PEM fuel cells, F_o and F_l are the parameters required as inputs to the model.

In this research, the performance of a PEM fuel cell (model IFC PC-29) is used. This performance is available from [66] in terms of a lower heating value (LHV) efficiency curve, which displays the relationship between the stack efficiency and the net power output in kW. To model the technical performance of the fuel processor, the LHV energy efficiency of a typical stream methane reformer (SMR) is used. This efficiency is defined as a ratio of LHV of hydrogen consumed to LHV of natural gas input, and is 75% for a typical steam methane reformer, according to [67]. Thus, the total fuel cell efficiency is determined by multiplying the fuel cell stack efficiency with the reformer efficiency.

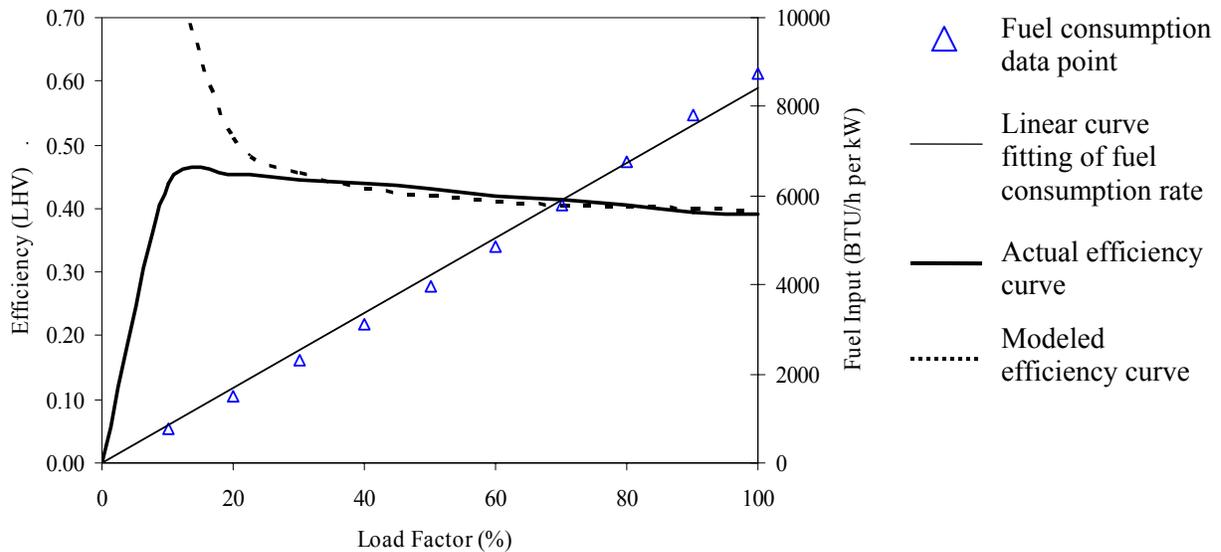


Fig. 11. Efficiency and fuel consumption characteristics of PEM fuel cells

Fig. 11 illustrates the total fuel cell efficiency curves (bold solid line), and fuel consumption data points (triangle shape) in BTU/h per kW on the y-axis versus the fuel cells load factor on the x-axis. The fuel consumption data points of PEM fuel cells are derived by dividing the energy

output from PEM fuel cells by the associated fuel cell efficiency. For example at the full load, overall efficiency of fuel cells is 39%. This implies fuel requirement of $3,413/0.39 = 8,571$ BTU per kW per hour.

Similar to IC engines, this fuel consumption curve is a linear function of its electrical power output. This research thus determines a linear curve-fit equation to represent the fuel consumption characteristic of PEM fuel cells, according to eq. 4-10, with different values of F_0 and F_1 than those of IC engines. The linear curve fitting of the fuel cells' fuel consumption characteristics is also shown in Fig. 11 (thin solid line).

Then, by converting the linear relationship of fuel consumption characteristics to the efficiency curve, the dashed line in Fig. 11 represents the modeled fuel cells efficiency curve. Since the efficiency curve of fuel cells diverges below 30% of the rated power, the minimum generation of PEM fuel cells is assumed at 30 percent of its rating, so that the assumption of using a linear curve-fit of the fuel cells fuel consumption characteristic to represent its electrical efficiency holds. Interestingly, while the efficiency of IC engines increases with the load factor (see Fig. 10), that of PEM fuel cells decreases with the load factor (see Fig. 11).

E. Battery banks: Battery banks are electrochemical devices that store energy from other AC or DC sources for later use. The following assumptions are used to model battery bank: the charge and discharge current is limited at 10% of battery AH capacity [⁶⁸] and [⁶⁹]; the round-trip efficiency is 95%; the maximum state of charge (SOC_{max}) and minimum state of charge (SOC_{min}) of each battery are 100% and 20% of its AH capacity, respectively.

4.4 Optimization Problem

4.4.1 The objective function

The purpose of this section is to describe an optimization technique developed for the design of stand-alone hybrid energy systems. The stand-alone energy system in this research serves the isolated demand in remote villages. The design takes into account the 20-year system life cycle costs, environmental externality costs (NO_x, SO_x and CO₂ emissions), as well as system reliability. The results are optimal suggestion for optimum configurations based on locally available energy resources. The problem is formulated as a mixed-integer linear program, written in C++ with CPLEX as an optimizer.

The objective function to determine the optimal configuration of a hybrid energy system is illustrated in eq. 4-11.

Minimize:

$$\sum_j (C_j - S_j) \cdot X_j + \sum_j \sum_y \sum_s \sum_i ((\delta_j \cdot F_{jysi} + OM_{jysi} \cdot U_{jysi}) \times \theta_{ysi}) + \sum_m \sum_j \sum_y \sum_s \sum_i \alpha_m \times (EF_{jm} \times U_{jysi} \cdot \theta_{ysi}) \quad (\text{eq. 4-11})$$

where

- C_j : Summation of discounted capital cost of generating unit j (\$).
- S_j : Discounted salvage value of generating unit j (\$).
- δ_j : Discounted fuel costs of generating unit j
(\$/liter for IC engines – diesel oil; and \$/BTU for PEM fuel cells – natural gas).
- F_{jysi} : Fuel consumption rate of generating unit j , in year y , season s , and hour i
(liter/h for IC engines and BTU/h for PEM fuel cells).
- OM_{jysi} : Operation and maintenance cost of generating unit j (\$/kWh).
- θ_{ysi} : Number of operating hours in year y , season s , and hour i .
- α_m : Externality cost of emission type m (\$/lb).
- EF_{jm} : Emission factor of technology j , emission type m (lb/kWh).
- X_j : Decision variables, representing number of generating units j .
- U_{jysi} : Decision variables, representing energy output from unit j in year y , season s , hour i (kW in one hour).

The parameter F_{jysi} in eq. 4-11 is a linear function of its electrical power output, which is a decision variable (U_{jysi}). This relationship can be written as shown in eq. 4-12 to represent fuel consumption characteristics of IC engines and PEM fuel cells.

$$F_{jysi} = F_{j0} \times E_{ji} + F_{j1} \times U_{jysi} \quad (\text{eq. 4-12})$$

where

- F_{j0} : Fuel consumption rate of generating unit j at no load (liter/kW/h).
- F_{j1} : Incremental fuel consumption rate of generating unit j (liter/kWh).
- U_{jysi} : Hourly energy generation from generating unit j , year y , season s , hour i .

E_{ji} : Decision to turn generating unit j on or off (0 = off, 1 = on) in hour i .

From eq. 4-11 and eq. 4-12, there are three decision variables in the objective function: number of generating units of each type (X_j); power generation from each unit in each hour i (U_{jysi}); and decision to turn the fossil-fired engine on or off (E_{ji}). E_{ji} is 0 when the generating unit j is off; and E_{ji} is 1 when the generating unit j is on.

4.4.2 General constraints

A. Energy balance constraints: the hourly energy demand must be satisfied by the amount of energy generated from all distributed generation (DG) units. Parameter S^- tracks the amount of unserved energy in each hour. This constraint converts to the following equation, for all years y , seasons s , and hours i :

$$\sum_{j=ACsources} U_{jysi,load} + \eta_{inv} \times \sum_{j=DCsources} U_{jysi,load} + S^- \geq load_{ysi} \quad (\text{eq. 4-13})$$

B. Yearly generation constraints: for all DG units, their yearly generation may not exceed their availability. For all technologies type j ,

$$\sum_{s=1}^S \sum_{i=1}^I U_{jysi} \times \theta_{ysi} \leq avai_j \times 8760 \times P_j \times X_j \quad (\text{eq. 4-14})$$

C. Individual capacity constraints: for all DG units, their hourly outputs are limited by their total generating capacity. For all hours i ,

$$U_{jysi} = U_{jysi,load} + U_{jysi,batt} \leq P_j \times X_j \quad (\text{eq. 4-15})$$

D. Reliability constraint: the overall reliability of the designed system must be greater than a certain designed value (R).

$$1 - \frac{\sum_i S^-}{\sum_i load_{ysi}} \geq R \quad (\text{eq. 4-16})$$

4.4.3 Decision variables and constraints associated with PV arrays

Decision variables of PV array are $X_{j=PV}$, and $U_{jysi, j=PV}$. The former is an integer decision variable representing the number of PV panels, whereas the latter is a continuous decision variable representing power generation from PV array in year y , season s , and hour i . The following equation represents the effect of solar irradiance intensity, temperature, and inverter efficiency on the available PV output, as described in section 4.3 (A).

$$U_{j=PV}^{jysi} = U_{j=PV}^{jysi,load} + U_{j=PV}^{jysi,batt} = P_{j=PV} \times \eta_{inv} \times \left(\frac{E_{ysi}}{E_0} \right) \times \left(1 - T_c \cdot (T - 25^\circ) \right) \times X_{j=PV} \quad (\text{eq. 4-17})$$

Where $P_{j=PV}$ is the rated power available from a PV panel in hour i ; η_{inv} is the inverter efficiency; E_{ysi} is the solar irradiation in any year y , season s , and hour i ; E_0 is the solar irradiation at the standard condition (1000 W/m²); the second to last factor takes into account a temperature effect; and the last factor is the integer decision variable for the number of PV modules selected.

4.4.4 Decision variables and constraints associated with wind turbines

Decision variables of wind turbines are $X_{j=WT}$ (a integer decision variable representing a decision to select a number of wind turbines), and $U_{j=WT}^{jysi}$ (a continuous decision variable representing power generation from wind turbines in year y , season s , and hour i). The relationship between power output from a wind turbine and the input wind speed (WS_{ysi}) is shown in eq. 4-18.

$$U_{j=WT}^{jysi} = U_{j=WT}^{jysi,load} + U_{j=WT}^{jysi,batt} = \eta_{inv} \times \begin{cases} 0 & ; WS_{ysi} < 3.5 \\ a \times WS_{ysi}^2 + b \times WS_{ysi} + c & ; 3.5 \leq WS_{ysi} < 17.5 \\ a \times WS_{ysi}^2 + b \times WS_{ysi} + c \Big|_{WS_{ysi}=17.5} & ; 17.5 \leq WS_{ysi} < 18 \\ 130 & ; WS_{ysi} > 18 \end{cases} \quad (\text{eq. 4-18})$$

4.4.5 Decision variables and constraints associated with IC engines

Decision variables of IC engines are $X_{j=IC}$ and $U_{j=IC}^{jysi}$. The former is a integer decision variable representing a decision to select or not select an IC engine. The latter is a continuous decision variable, representing power generation from the IC engine in year y , season s , and hour i . The following equations represent the generation characteristic of an IC engine. They imply that the power generation from the IC engine at any hour i can take the value of zero, or any value between its minimum generation (which is assumed to be 30% of its rated power), and its maximum generation (which is its rated power), if the IC engine is selected. Where $P_{j=IC}$ is the rated power of an IC engine,

$$U_{j=IC}^{jysi} = U_{j=IC}^{jysi,load} + U_{j=IC}^{jysi,batt} \leq P_{j=IC} \times X_{j=IC} \quad (\text{eq. 4-19})$$

$$\begin{aligned} U_{j=IC}^{jysi} = U_{j=IC}^{jysi,load} + U_{j=IC}^{jysi,batt} &= 0 \quad \text{or} \\ &= [0.3 \times P_{j=IC} \times X_{j=IC}, \quad P_{j=IC} \times X_{j=IC}] \end{aligned} \quad (\text{eq. 4-20})$$

4.4.6 Decision variables and constraints associated with PEM fuel cells

Similar to IC engines, decision variables of PEM fuel cells are $X_{j=FC}$ and $U_{jysi, j=FC}$. The former is an integer decision variable representing a decision to select or not select a PEM fuel cell. The latter is a continuous decision variable, representing power generation from the PEM fuel cell in year y , season s , and hour i . The following equations represent the generation characteristic of a PEM fuel cell. They imply that the power generation from the PEM fuel cell at any hour i can take the value of zero, or any value between its minimum generation (which is assumed to be 30% of its rated power) and its maximum generation (rated power), if the PEM fuel cell is selected.

$$U_{jysi, j=FC} = U_{jysi,load, j=FC} + U_{jysi,batt, j=FC} \leq \eta_{inv} \times P_{j=FC} \times X_{j=FC} \quad (\text{eq. 4-21})$$

$$U_{jysi, j=FC} = U_{jysi,load, j=FC} + U_{jysi,batt, j=FC} = 0 \quad \text{or} \quad (\text{eq. 4-22})$$

$$= [0.3 \times \eta_{inv} \times P_{j=FC} \times X_{j=FC}, \eta_{inv} \times P_{j=FC} \times X_{j=FC}]$$

4.4.7 Decision variables and constraints associated with battery banks

Typically, the storage capacity of a battery is measured in terms of its ampere-hour (AH) capacity. Decision variables of a battery are $X_{j=batt}$ (an integer decision variable representing the number of batteries), and $U_{jysi, batt}$ (a continuous decision variable representing power output from the battery or $U_{batt,load}$ in year y , season s , and hour i).

The constraints that represent the maximum allowable charge and discharge current to be less than 10% of battery AH capacity are shown in the following equations, respectively.

$$\sum_{j=DCsources} U_{jysi,batt} + \eta_{inv} \times \sum_{j=ACsources} U_{jysi,batt} \leq (0.1 \times V_{sys} \times P_{j=batt} \times X_{j=batt}) \quad (\text{eq. 4-23})$$

$$U_{jysi,load, j=batt} \leq (0.1 \times V_{sys} \times P_{j=batt} \times X_{j=batt}) \quad (\text{eq. 4-24})$$

where the parameter V_{sys} is the system voltage at the DC bus; and the parameter $P_{j=batt}$ is the battery capacity in AH. The state of charge (SOC) of the battery at any hour i can be obtained by monitoring the charge/discharge energy from the battery, as shown in eq. 4-25.

$$SOC_i = SOC_{\max} - \sum_{n=0}^i \left(U_{jysi,load, j=batt} \right) + \sum_{i=0}^i \left(\sum_{n=DCsources} U_{jysi,batt} + \eta_{inv} \times \sum_{j=ACsources} U_{jysi,batt} \right) \quad (\text{eq. 4-25})$$

It is important that the *SOC* of the battery in any hour *i* be monitored to prevent the battery from overcharging or undercharging. The associated constraints can be formulated by comparing the battery *SOC* in any hour *i* with the battery SOC_{\min} and the battery SOC_{\max} , as shown in eq. 4-26. This research assumes that SOC_{\min} and SOC_{\max} equal 20% and 100% of the battery AH capacity, respectively. It is also assumed that the initial *SOC* of the battery is 100% at the beginning of the simulation.

$$\begin{aligned} SOC_i &\leq SOC_{\max} \\ SOC_i &\geq SOC_{\min} \end{aligned} \quad (\text{eq. 4-26})$$

Lastly, in order for the system with battery to be sustained over a long period of time, the battery *SOC* at the end of the simulation period must be greater than a given percentage of its SOC_{\max} . This study assumes 90%, as shown in eq. 4-27.

$$SOC_{i=n} \geq 0.9 \times SOC_{\max} \quad (\text{eq. 4-27})$$

4.5 Conclusions

This chapter presents the optimization model used to design the optimal configuration of hybrid energy systems, taking into account system life cycle cost, available resources, environmental costs and reliability requirements. A mathematical model of each power generating technology is also described, along with decision variables and associated constraints. It is important to note that the designed system is greatly dependent on locally available solar and wind resources. This research recommends the use of solar and wind resources that represent the typical meteorological year (TMY) data sets. Because the data sets represent typical weather conditions rather than extreme conditions, they will make it possible to get a more accurate design of solar energy systems. Solar insolation data sets for the U.S. sites are available at: http://rredc.nrel.gov/solar/old_data/nsrdb/tmy2.

Chapter 5

Computer Algorithm for the Verification of Power Solutions

The chapter presents a simple dispatch algorithm that verifies the operation of the designed power solution. The dispatch algorithm determines whether or not the designed power solution can meet the demand at the level of required reliability. The amount of energy not served is used as an index to compare the energy not served that results from simulating the operation of the designed power system, to the design criteria, i.e. EENS = 0%, 10%, or 20%. Section 5.1 introduces the basic concept of a hybrid controller. Then, all possible dispatch strategies that result in the least-cost operation are presented in section 5.2. Section 5.3 describes the implemented dispatch algorithm.

5.1 Dispatch Concepts

A dispatch strategy for a hybrid power system is defined as a control algorithm for the interaction among various system components. Fig. 12 shows a simple block diagram of a hybrid controller.

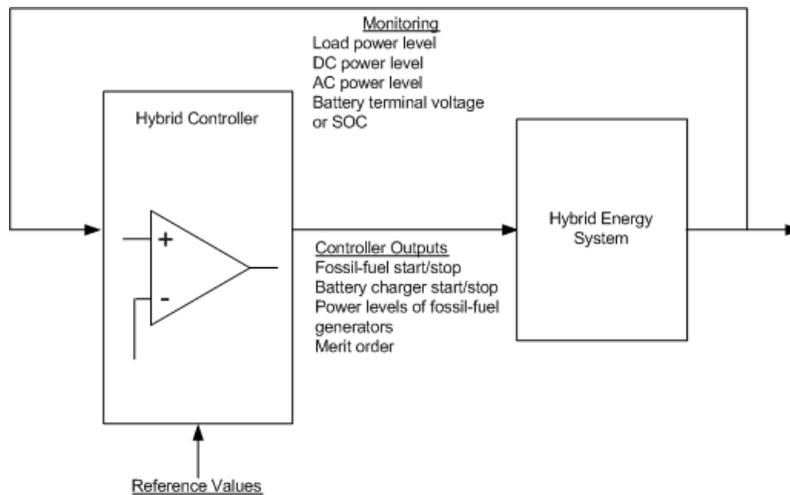


Fig. 12. Hybrid system controller block diagram

The hybrid system controller typically works as follow: the hybrid controller (the left block in Fig. 12) monitors real time data from the hybrid energy system, like load power levels, generator power levels, and battery terminal voltage, or battery SOC. The data is compared to the default values or the reference values. This comparison results in appropriate output signals to control and operate the system, i.e. fossil-fuel start/stop signals and battery charger start/stop signals.

5.2 Analysis of Possible Dispatch Strategies

5.2.1 Analysis of the Objective Function

In the objective function of the hybrid system optimization problem shown in eq. 4-11, the total system life cycle cost is minimized. The total system life cycle cost is composed of the capital costs of all generating technologies, and their fuel costs. Regarding the latter, the determination of the fuel costs for IC engines or PEM fuel cells depends on a linear function of hourly energy output. For example, the total fuel cost (\$) of the engine from time t_0 to t_i is the product of fuel cost (\$/liter) and total fuel consumption (liter) from t_0 to t_i , as shown below.

$$\begin{aligned}\text{Total cost of fuel} &= C_f \times \int_{t=t_0}^{t_i} (F_0 + F_1 \cdot U(t)) dU(t) \\ &= C_f \times \sum_{t=t_0}^{t_i} (F_0 + F_1 \cdot U(t)) ; \text{ for discrete representation} \\ &= C_f \times \left[F_0(t_i - t_0 - t_{OFF}) + F_1 \cdot \sum_{t=t_0}^{t_i} U(t) \right]\end{aligned}$$

This implies that, for the same given demand, to minimize the engine's fuel cost is to minimize the engine's run time. Thus, for any two cases, as long as (i) total engine's energy output ($\sum U(t)$) is the same and (ii) the length of the operating period is the same ($t_i - t_0 - t_{OFF}$), there will be no restriction on which hours and how much energy to charge the battery because they will result in the same fuel cost.

5.2.2 Possible Dispatch Strategies

In a system that has PV or WT, the output from these renewable generators is generally subtracted from the total demand to determine the net load. By observing hourly operation of hybrid energy systems from the hybrid system optimization problem developed in Chapter 5, there are four possible dispatch strategies to meet the net load. The combination of these strategies results in the least-cost operation of the designed hybrid energy system.

These strategies are:

- a) Battery operation strategy – the use of only the battery to cover the demand.
- b) Cycle charging strategy – the engine is ON to cover the demand and charge the battery.

- c) Load following – the engine is ON to follow the load, no charge to the battery and no discharge from the battery.
- d) Peak shaving strategy – the use of the battery to shave the peak demand.

When the net demand is low, two strategies are always selected. These include the battery operation strategy and the cycle charging strategy. The ideal optimization results indicate that the use of the battery to power low net demand is always selected when fossil-fuel generators are OFF. It is also possible that, during low load, diesel generators generate power at higher loading rate and use the excess energy to charge the battery. The energy generated from the engine, if it is ON, is not allowed to be lower than its minimum generation.

When the net demand is high, two possible dispatch strategies are always selected. These are the cycle charging strategy and the load following strategy. The cycle charging strategy, which is discussed above, is generally used in combination with the load following strategy. The decision to use one or the other strategy, i.e. the decision to generate power equal to the load (load following) or greater than the load to charge the battery (cycle charging), can be arbitrary selected, as explained in the last paragraph of section 5.2.1.

Lastly, the peak shaving strategy is the simultaneous operation of both battery and fossil-fuel generators. The battery helps the generators to power the load during the peak period. This strategy is typically used when fossil-fuel generators alone cannot meet the demand. This case happens only when the net demand is typically greater than the capacity of fossil-fuel generators.

5.3 Implemented Dispatch Algorithm

Fig. 13 through 17 describe the computer algorithm to simulate the operation of the designed power system. The following items summarize key characteristics of the implemented dispatch strategy.

According to Fig. 13,

- Energy output of PV is calculated according to eq. 4-17 to include the effect of solar insolation and temperature that are different from the standard test condition, as well as inverter efficiency.
- Energy output of WT is calculated according to eq. 4-18 to represent the relationship between wind speed and AIR403 power output.
- Energy output from PV and WT is treated as a negative load, so the Netload – the different between the actual load and renewable energy output – can be determined. If the

output from PV and WT is greater than the load, the excess energy is directed to charge the battery ($U_{batt, in}$).

- The charge and discharge energy to and from the battery is limited by ChargeLim, which is assumed at 10% of total AH battery capacity.

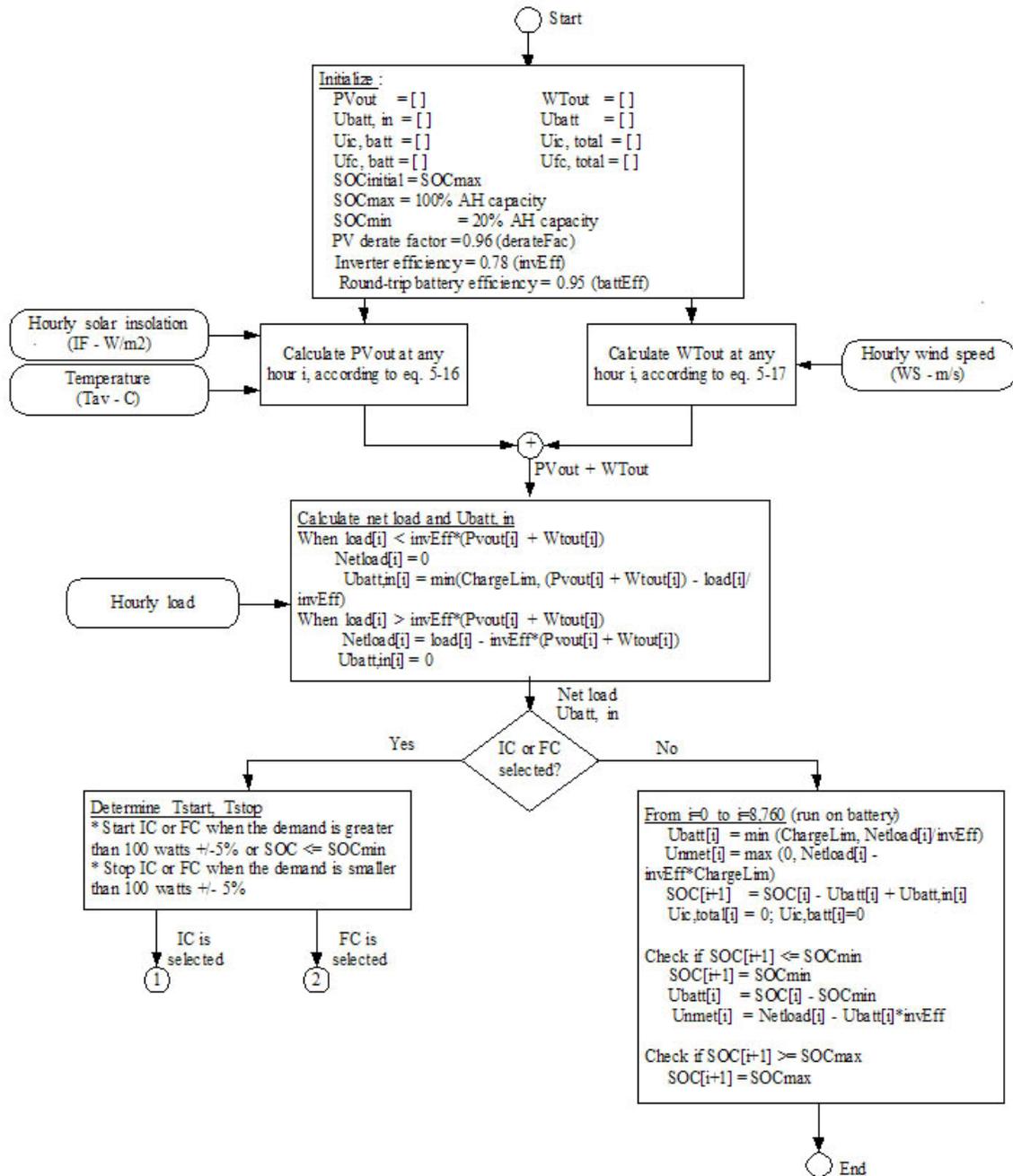


Fig. 13. Dispatch algorithm: Part I

- If the designed system does not have an IC engine or a PEM fuel cell, then Netload can only be served only by the battery. The discharge energy from the battery is limited by ChargeLim. If the battery SOC is below SOC_{min}, no further discharge is allowed. Thus, there will be a portion of demand unmet.
- If either an IC engine or a PEM fuel cell is selected, T_{start} (time to start the engine) and T_{stop} (time to stop the engine) must be determined for each day.

According to Fig. 15, if the system has battery storage and either an IC engine or a PEM fuel cell, the operation characteristic will be divided according to the time that the engine starts or stops. The following description explains the operation of the IC engine in Fig. 15 (left) during $t=0$ to $t=T_{start}$; during $t=T_{start}$ to $t=T_{stop}$; and during $t=T_{stop}$ to $t=24$ of each day. The only difference between the use of IC engines and the use of PEM fuel cells is the effect of inverter efficiency because an IC engine produces AC output, whereas a PEM fuel cell produces DC output.

During $t=0$ to $t=T_{start}$ of each day: the system is only operated on the battery. This is called the battery operation strategy.

- Energy discharged from the battery (U_{batt}) must be enough to serve hourly demand, i.e. Netload/invEff, but not be greater than the maximum allowable discharged energy from the battery (ChargeLim).
- Unmet energy (Unmet) is zero if the discharge energy from the battery can cover the Netload. Otherwise, unmet energy is determined by subtracting the Netload from ChargeLim*invEff.
- SOC of the battery at any hour i is determined according to eq. 4-25.
- No energy is generated from an IC engine or a PEM fuel cell during this period. However, whenever SOC reaches SOC_{min}, the engine must be started in order to cover the demand and charge the battery. This algorithm is shown in Fig. 14.

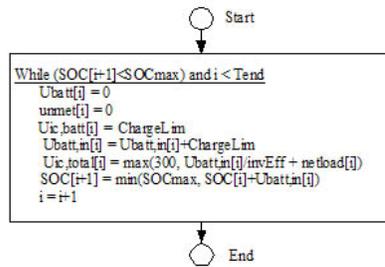


Fig. 14. Algorithm to check SOC

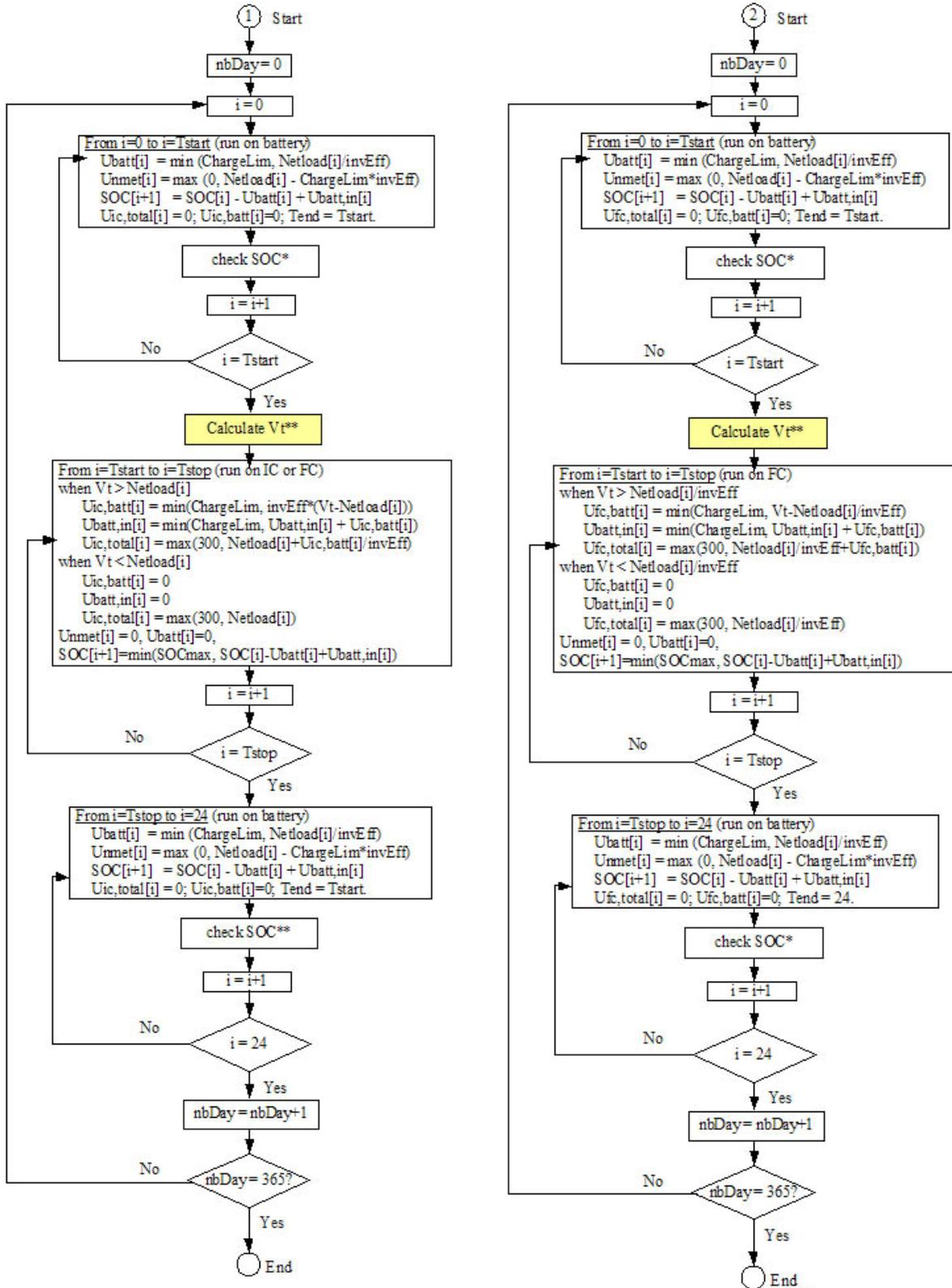


Fig. 15. Dispatch algorithm: Part II (* see Fig. 14; ** see Fig. 17)

During $t=T_{start}$ to $t=T_{stop}$ of each day: the system is operated on the engine to cover the load and to charge the battery.

- It is assumed that, during this period (from T_{start} to T_{stop}), the power level that the engine generates is at V_t if the net load is less than V_t and if V_t is greater than the minimum generation (cycle charging strategy). If V_t is less than the minimum generation, the power level that the engine generates equal to its minimum generation. If the net load is greater than V_t , the engine generates power at the net load (load following strategy). See Fig. 16.
- V_t is the power level that can cover the net load and fully charge the battery from T_{start} to T_{stop} . Fig. 17 illustrates the algorithm to determine V_t .
- If V_t is greater than the net load, the difference between V_t and the net load goes to charge the battery. This charge energy is subjected to the charge limit of the battery of ChargeLim. On the other hand, if V_t is less than the net load, the energy to charge battery is zero.
- Since the system is operated from the engine, there is no discharge from the battery and no unmet demand during this period. It is assumed in this case that the engine size is always greater than the peak demand.
- Again, battery SOC in every hour is calculated according to eq. 4-25.

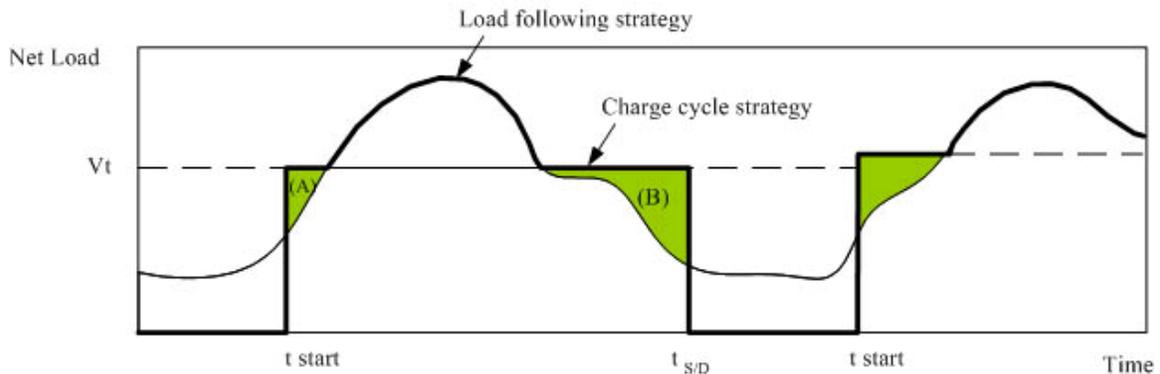


Fig. 16. During T_{start} and T_{stop} , the power level of the engine is at V_t (if V_t is greater than the net load and the engine's minimum generation); the power level of the engine equals the net load (if V_t is less than the net load). To determine V_t , energy represented in areas (A) and (B) must fully charge the battery.

During $t=T_{stop}$ to $t=24$ of each day: the system is operated from the battery, so the algorithm is the same as that during $t=0$ to $t=T_{start}$ of each day (battery operation strategy).

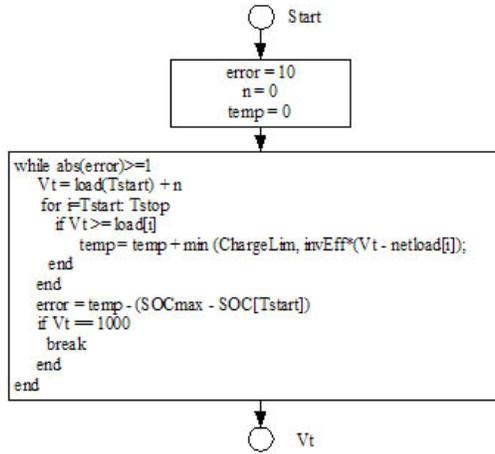


Fig. 17. Algorithm to determine V_t

5.4 Conclusions

This chapter introduces a dispatch algorithm to determine the amount of unmet demand of the designed hybrid energy system. The objective of this algorithm is to verify if the designed power system, when operating using the traditional dispatch strategy, can meet the demand at the required reliability level. Note that for the traditional dispatch strategy, the net load is determined by subtracting the energy produced by renewable energy generators from the hourly demand. The net load is then covered by the battery or the engine, if the latter is available. The presented dispatch algorithm is implemented in Chapter 8.

PART III: A CASE STUDY OF A DEVELOPING COUNTRY

Chapter 6

Country Background and Choice of Technologies

This chapter reviews existing IT infrastructures in a remote area of a developing country used as a case study – Chittagong and Chittagong Hill Tracts, Bangladesh. Then, section 6.2 illustrates the problem of lacking Internet and power access in this area by identifying network gaps. In section 6.3, in order to identify the most cost-effective technology to bridge the last-mile gap, alternate telecommunication technologies are compared with respect to their cost of ownership, available bandwidth, and coverage area in the context of Bangladesh. Section 6.4 briefly discusses the need to upgrade national backbone.

6.1 Basic IT infrastructures in Bangladesh

Bangladesh is a developing country with extremely poor telephone density and a low number of Internet users. In 2003, those numbers are 0.51 telephone lines per 100 inhabitants and 0.03 Internet users per 100 inhabitants ^[70], respectively. At present, Bangladesh Telegraph and Telephone Board (BTTB) is the only government-owned PSTN service provider in the country. BTTB assumes the role of natural monopolist for the provision of basic telephone services, including national long distance, and international long distance services. So far, PSTN infrastructure has been inadequately provided by BTTB. As for an example, on average only 2 of 10 telephone calls are successfully completed ^[71]. The telephone installation charge in Bangladesh is also prohibitively expensive. While the country's GDP is only \$350, the charge is roughly \$200 ^[72] for a new telephone line.

Satellite is the only way to communicate internationally since Bangladesh has not been connected with the submarine optical cable link SEA-ME-WE 3. There are four satellite earth stations established by BTTB located at Betbunia, Talibabad, Mohakhali and Sylhet. In early 2004, the government has negotiated to join the submarine cable project SEA-ME-WE 4 that will link Bangladesh to the world via Cox's Bazar by 2005. This connection will provide Bangladesh with large and reliable bandwidth, at least 20 times as much capacity as Bangladesh currently has ^[73]. This connection will be an excellent infrastructure to support Internet expansion to several last-mile areas in Bangladesh.

At present, microwave links are the core telecommunication network of the country. All small administrative units are connected with their district headquarters through microwave, UHF and

VHF radio links. This is due to a Bangladesh landscape dominated by rivers and canals. Disadvantages of microwave links are the low data transmission rate and unreliable connection. The data rate of microwave links in Bangladesh ranges from 34 - 155 Mbps. Signal strength and quality of these microwave links are often affected by weather conditions, such as rain and thunderstorms [74].

The BTTB's backbone then is transferred from microwave links to optical fiber links, which are only available in cities. Most optical fiber cable is installed along the country's national railway network. Existing optical fiber backbone is composed of a 276-km STM-16 link, connecting Dhaka-Comilla-Feni-Chittagong; a 800-km STM-4 connecting Bogra-Palashbari -Rangpur; and a 1,000-km STM-1 connecting Rangpur-Saidpur-Dinajpur-Thakurgaon-Pachagarh. Planned fiber routes are 622Mbps links, connecting Dhaka-Gazipur-Mymensingh-Tangail-Sirajgonj-Bogra and B.Barua-Shahjibazar-Moulavibazar-Sylhet; and a 155Mbps link, connecting Chittagong and Cox's Bazar [74] (to be connected with SEA-ME-WE 4 cable in 2005). See Table 2 for standard and data rate of optical fiber. The maps of existing microwave and fiber optic routes in Bangladesh are available in the BTTB annual report 2001 [www.bttb.net].

Table 2. Optical fiber standard and data rate

Optical fiber standard	Data Rate
STM-1 or OC-1	155 Mbps
STM-4 or OC-12	622 Mbps
STM-16 or OC-48	2.488 Gbps

To spread a telecom footprint across the country, the current strategy is to have optical fiber links leased by a private mobile phone operator. As a result, the mobile industry of Bangladesh has built large coverage along the country's railway networks and has superseded the fixed telephone network since 2001. There are four private mobile operators in Bangladesh, which are GrameenPhone (GP), TMIB (Aktel), PBTL (CityCell), and Sheba. Please visit [75] for the cellular phone coverage map of each operator in Bangladesh. In 2004, the total length of GP optical fiber is 2,000 km and the maximum capacity is 622 Mbps. This successful story is, however, hampered by the insufficient interconnections at the subscribers' end as mentioned earlier. Current situation is that mobile phone users are often unable to call fixed telephone users, but they are only able to communicate among themselves.

Another telecommunication infrastructure available in Bangladesh is the fiber optic over high-voltage transmission line. The main purpose of this power line communication (PLC), which connects all the power plants and high-voltage substations with the load dispatch center, is to perform SCADA and economic dispatch. The Bangladesh Power Development Board (BPDB) is also planning to utilize this fiber resource to facilitate the backbone communication throughout the country. At present, 448 km of optical fiber has already been installed around Dhaka and on the Dhaka-Chittagong route. More information about PLC can be found at [76].

6.2 Identifying Network Gap

In summary, Bangladesh possesses all necessary IT infrastructures; however, the readily available infrastructures are merely concentrated in major cities and towns. This results in a low teledensity in Bangladesh, especially in remote locations. In order to portray this fact, the IT network gap is approximated in Chittagong and Chittagong Hill Tracts as shown in Fig. 18.

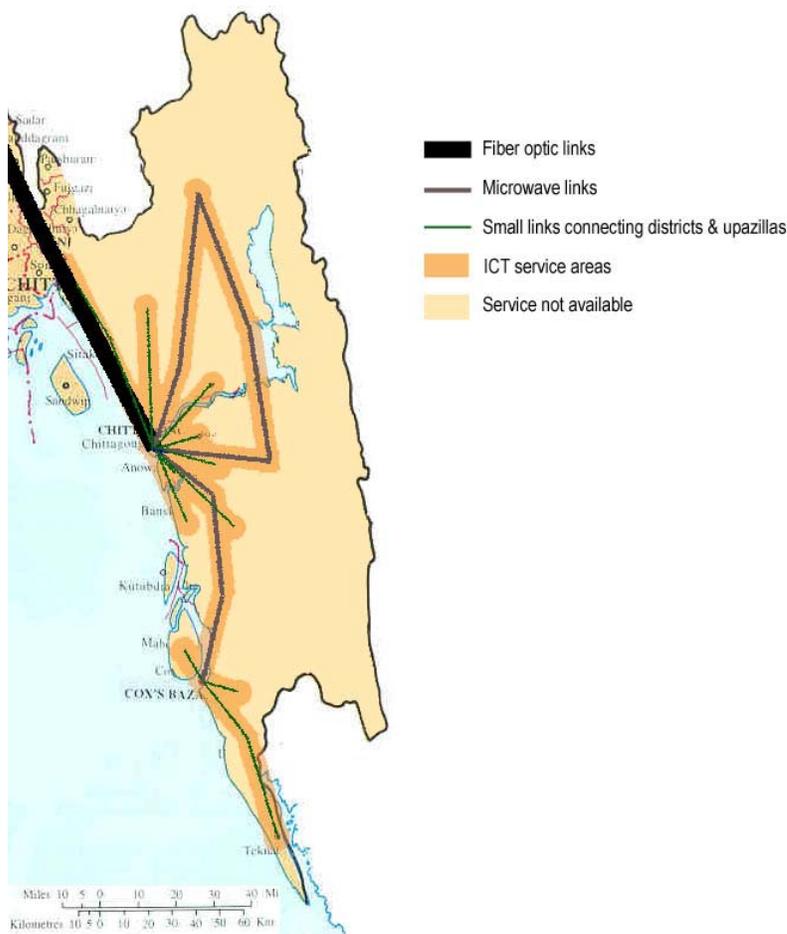


Fig. 18. Network gap in Chittagong and Chittagong Hill Tracts

The gap is estimated by assuming that telephone and Internet services are available as far as 5 km from the existing IT infrastructures, which are existing fiber optic links, microwave links, and small links connecting districts and upazillas – an administrative region lower than the district level.

According to Fig. 18, most of the areas that the IT services are not available are, however, located less than 35 km from the PSTN connection, i.e. at existing microwave stations. Thus, in order for the country to improve its teledensity numbers, Bangladesh has to expand necessary telecommunication infrastructures to last-mile areas, providing Internet backbone to each remote access point throughout the country, and making local power access available.

The first and second tasks can be done by exploring alternate technologies capable of providing high-speed Internet that is not economically and technologically beyond the reach of most people. Identifying the suitable technology for Bangladesh is a topic of section 6.3. In addition, locations of base station installation and routes to extend fiber backbone that can cost-effectively bridge the last-mile gap must be identified. This is related to the implementation of the telecom optimization model, which is discussed in Chapter 7. In addition to expanding the IT infrastructure to last-mile areas, electricity power must be provided so the Internet can be used. This third task can be done by exploring the least-cost configuration of power generating technologies capable of harnessing locally available resources. This is related to the implementation of the power optimization model, presented in Chapter 8.

6.3 Comparison of Alternate Technologies

Descriptions of alternate telecommunication technologies have been summarized in Chapter 2. It is apparently that wireline solutions (POTS, DSL and cable modem) are not cost-effective in most remote locations because they usually have the distance limitation of 2-5 km from the PSTN. Since wireless technologies offer lesser investment costs for a larger coverage area, and shorter deployment time than wireline alternatives, wireless technologies are of major focus in this study.

Four last-mile options (WLL, MMDS, 802.16 and VSAT) are compared in Table 3 in terms of the cost of ownership and the cost of ownership per bandwidth (kbps) available at the base station. 802.11, 802.20 and WWAN are disregarded in this study. This is because 802.11 has short distance limitation, 802.20 is not yet available, and WWAN must rely on existing cellular network (which does not exist in the area of interest).

Table 3. Cost of ownership at different levels of remoteness (See Appendix B for detail)

Options	Max Speed at the Base Station	Max Data Rate (each subscriber)	Distance from LE				Cost (\$)	Cost/kbps available at the base station
			0-10 km	10-20 km	20-35 km	>35 km		
MMDS*	3 Mbps	128/256 kbps	☺	☺			\$839,350	\$273
WLL*	2 Mbps	35/70 kbps	☺	☺	☺		\$470,830	\$229
802.16*	192 Mbps	24 Mbps	☺	☺	☺		\$1,603,067	\$8
VSAT**	2 Mbps	2 Mbps				☺	\$87,500	\$42

* The costs for MMDS, WLL and 802.16 are calculated based on 1,000 subscribers, excluding access costs to the national PSTN; ** The cost of VSAT is based on 1 subscriber.

From Table 3, based on the cost of ownership per bandwidth at the base station, 802.16 is the most promising and cost-effective technology to bridge the digital divide. Thanks to its broadband capability, one subscriber line can be shared with 10 or more computers and this will bring the cost further down. On the other hand, WLL could be an affordable solution when high-speed connection is not a requirement since the cost per subscriber (approximately \$470 per subscriber) is the lowest among these four technologies.

6.4 Need for Upgrading the National Backbone

As already mentioned, microwave links in Bangladesh can only offer the maximum bandwidth of 34-155 Mbps and VSAT dishes can only offer the maximum bandwidth of 2 Mbps. It is obvious that these speeds will not be sufficient to serve future needs. This is because, for 802.16 to support each user at the speed of 24 Mbps, it requires the aggregated bandwidth at the base station of 192 Mbps. Thus, the national backbone needs to be upgraded in order to support the additional bandwidth required by the last-mile technology to be installed. The most effective way to upgrade the national backbone is to extend optical fiber to the new base stations. This will also provide more reliable connection and higher data transmission capability in the long run.

Despite its future benefits, the required lead time of optical fiber installation can be a few years depending on the length of the cable to be installed. For immediate implementation, a VSAT system could provide PSTN connection at a selected base station location that does not have access to the national PSTN, i.e. no existing microwave link. At the same time, optical fiber could be extended to that location in order to serve the growing demand.

Illustrated in Fig. 19 is the break-even line of the cost to extend the optical fiber versus the cost of a VSAT system in Bangladesh context, based on the cost for a fiber extension on railway network of \$4,100/km^a and on highway network of \$7,188/km^a. Similarly, Fig. 20 converts the X-axis of Fig. 19 (the total VSAT system costs) to number of months that a VSAT dish is in operation, based on the VSAT dish cost of \$75,000, and the monthly charge of \$8,000.

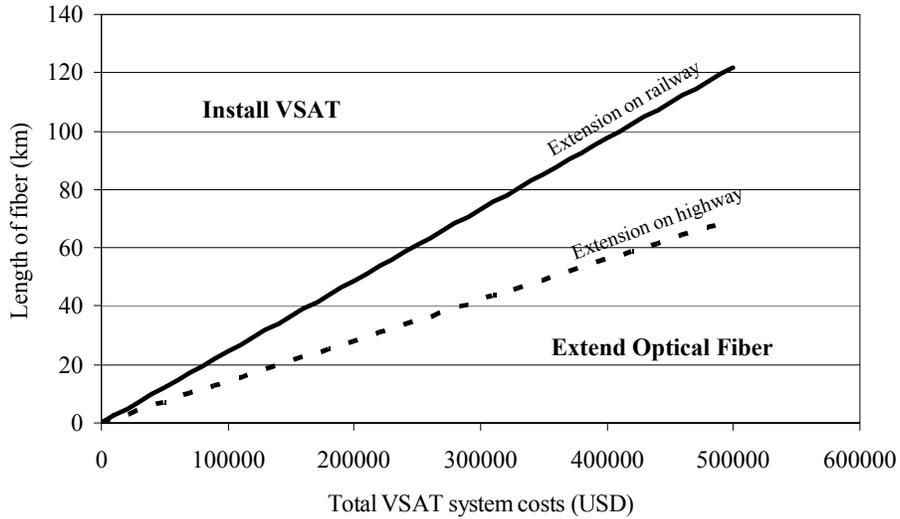


Fig. 19. Break-even line of the cost to extend optical fiber versus the cost of a VSAT system

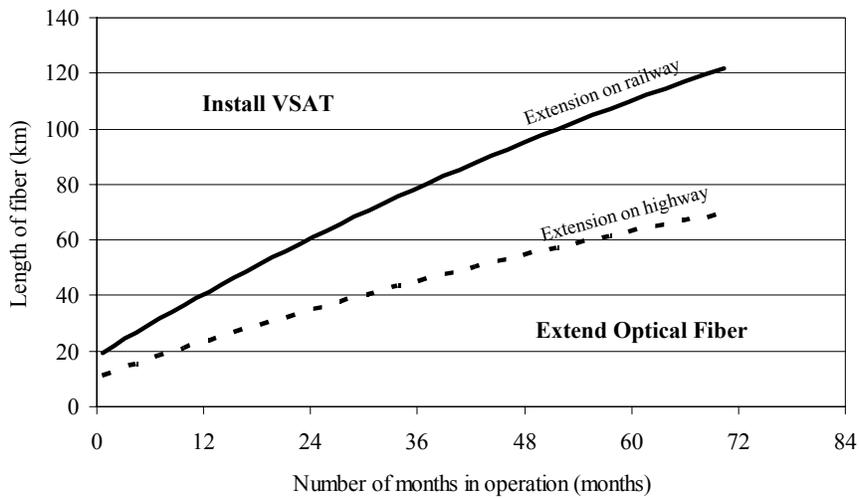


Fig. 20. Break-even line comparing length of optical fiber versus number of months in operation of VSAT

^a \$4,100/km = \$1,250/km+\$2,850/km and \$7,188 = \$1,250/km+\$5,938/km; where \$1,250/km is the cost of 12-strand single mode fiber; \$2,850/km is the cost to lay fiber on railway tracks; and \$5,938/km is the cost to lay fiber on highways routes. See Table 3 for the cost assumptions in Bangladesh context.

According to Fig. 19 and Fig. 20, extending optical fiber along railway line for 40 km, for example, is equivalent to the investment cost of $40 \times \$4,100 = \$164,000$. This is also equivalent to purchasing and operating a VSAT dish for about 12 months [b]. Since the cost of a VSAT system is also expensive, this plot will help decision makers to reach a decision whether or not VSAT should be set up as a near-term solution for PSTN access.

6.5 Conclusions

This chapter reviews existing IT infrastructures in Bangladesh, identifies network gaps in Chittagong and Chittagong Hill Tracts, and suggests the most cost-effective telecommunication technology to bridge the digital divide. Four last-mile alternatives are compared with respect to their data rate, coverage distance and investment costs per line per kbps (based on 1,000 lines). The comparison indicates that 802.16 and WLL are very cost-effective to bridge the last-mile gap. The selection between these two alternatives will depend on the speed requirement and the ability to pay for the service. If 802.16 is selected, the national back bone needs to be upgraded in order to be able to support new bandwidth required by the new last-mile base station, so that the end-user can fully utilize the available capacity of 802.16 at 24 Mbps each subscriber.

^b This number can also be calculated by solving for n, according to the following equation:

$$164,000 = 75,000 + \left(\frac{(1+i)^n - 1}{i(1+i)^n} \right) \times 8000;$$

where i is a monthly interest rate (0.1/12) and n is number of months

Chapter 7

Expanding Country-Wide Internet Access

Having identified the problem and technologies that can cost-effectively bridge the digital divide in the previous chapter, this chapter implements the developed methodology in Chapter 3 to produce a Telecom-and-Internet access map in an area of interest. To begin with, data used and assumptions are discussed in section 7.1. Then, section 7.2 describes the implementation of the telecom optimization model in the case study of Bangladesh. Section 7.3 presents three case studies.

7.1 Technology and Cost Assumptions

A. Technology Assumptions:

The 802.16 is the wireless technology selected to provide ICT service to remote villages as discussed in Chapter 6. The wireless coverage is assumed to be a perfect circle of 35-km radius.

B. Equipment cost assumptions [77]:

Investment costs used for 802.16 are in the context of Bangladesh as of June 2004. The total investment costs are \$77,984. These include an access point, four 5.8GHz 16dbi 90° sector antennae, a cable with connectors for the access point, a surge suppressor for 5.8GHz, an Ethernet surge suppressor, and installation charge at Chittagong. The type of tower selected for base stations is a self-supporting tower that allows easy antenna masting and maintenance for sectoral structure of the base stations. Approximate cost of a 160ft self-support tower is \$9,000. However, if new base stations are installed at existing microwave stations, the tower cost can be neglected.

C. Fiber cost assumptions [78]:

Costs of optical fiber extension are composed of cost of fiber cable and cost of construction. With respect to the former, it is assumed that the cable used is 12-strand single-mode fiber. The cost of 12-strand single-mode fiber is \$1,250/km based on the U.S. market. This cost is roughly the same from installation to installation. With respect to the latter, it is assumed that “pull-through” technique is used to lay fiber along railway tracks, and “bury” technique is used to lay fiber along highway routes. Based on the U.S. market, the cost to lay fiber using “bury” technique is estimated at \$25,000/km. The cost to lay fiber using “pull-through” technique is estimated at \$12,000/km. The cost to lay fiber comprises labor cost, equipment cost, and right-of-way cost, as

shown in eq. 7-1. A typical breakdown of costs for typical trenching in the U.S. is labor ($C_{labor,US}$: 80-85%), equipment ($C_{equipment,US}$: 5-10%), and right-of-way ($C_{row,US}$: 5-10%).

$$C_{fiber} = C_{labor} + C_{equipment} + C_{row} \quad (\text{eq. 7-1})$$

The cost of laying fiber must be converted to the cost in Bangladesh context. It is assumed that equipment cost and right-of-way cost remain constant, but the labor cost in the U.S. context must be converted to the cost in Bangladesh context using a ratio of GDP_{PPP} (gross domestic product: purchasing power parity). Thus, the cost to lay fiber in Bangladesh context can be written in eq. 7-2.

$$C_{fiber,BD} = \left(\frac{GDP_{PPP,BD}}{GDP_{PPP,US}} \right) C_{labor,US} + C_{equipment,US} + C_{row,US} \quad (\text{eq. 7-2})$$

Table 4 summarizes costs parameters used in the model.

Table 4. Component costs and economic assumptions

Items	One-time costs (\$ in Bangladesh Context)
Equipment of 802.16	\$77,984
160 feet self-supporting tower	\$9,000
	\$0 if new base stations are setup at existing microwave stations
12-strand single-mode fiber	\$1,250/km
Cost to lay fiber on railway tracks	\$12,000/km in U.S. context
Cost to lay fiber on highway routes	\$25,000/km in U.S. context
2001 GDP per capita (PPP) Bangladesh	\$1,610
2001 GDP per capita (PPP) US	\$34,320
Cost to lay fiber on railway tracks	\$2,850/km in Bangladesh context
Cost to lay fiber on highway routes	\$5,938/km in Bangladesh context
Annual maintenance cost**	10% of 802.16 equipment cost annually
Data service provider license from BTRC**	\$3,333.3 annually*
Cost of E1 access charge from PSTN at 2 Mbps **	\$1,266.7 annually*

*Assuming \$1 = 60Tk; **Excluded from the optimization model

D. Cost excluded form the analysis:

The costs that are excluded from the analysis include recurring costs: (i) maintenance costs of 802.16, which is charged at 10% of its investment costs [⁷⁹]; (ii) a data service provider license from BTRC, which is roughly Tk. 200,000 per annum; and (iii) an annual E1 access charge at 2 Mbps, which is Tk. 76,000 per annum [⁸⁰]. Leasing 2 Mbps from BTTB at the beginning is reasonable because later this bandwidth can be increased along with the demand. The following costs are also excluded: site acquisition and clearance from concerned authorities, VAT, and other government levies.

E. GIS data sources:

The GIS data required as inputs are political boundary and population density of the country of interest, railway network, and highway network. The political boundary, railway and highway network data of Bangladesh in e00 format are available for free download at the GIS data depot [⁸¹]. The population density data are available from the United Nation website [⁸²].

F. Locations of source and destination nodes:

In addition to the above GIS data sets, latitudes and longitudes of source and destination nodes are needed as inputs from a user. In this case study, source nodes are arbitrarily chosen to be at the locations (91.9320°, 22.3560°) and (91.7970°, 22.4700°). A set of destination nodes distributed along railways and highways is selected by the model. An additional set of destination nodes is given to the model at the locations of existing microwave stations. These locations are estimated at (91.1550°, 23.2535°), (92.1307°, 22.6508°), (92.0820°, 22.0786°), (92.2829°, 22.0664°), (92.0759°, 22.7744°), and (92.0576°, 21.5185°).

7.2 Model Implementation with a Case Study of Bangladesh

Since all data sets do not come in the same formats or coverage regions, the first task is to convert them into the same standard format, and the same region.

A. Extract population density: This task is to convert the population density data available in south-Asian countries to the population density in the country of interest as shown in Fig. 21. Bangladesh has the south bounding coordinate of 20.55°N, the north bounding coordinate of 26.73°N, the west bounding coordinate of 87.98°E, and the east bounding coordinate of 92.92°E. The given data set has the south bounding coordinate of 5°N, the north bounding coordinate of 43°N, the west bounding coordinate of 43°E, and the east bounding coordinate of 98°E.

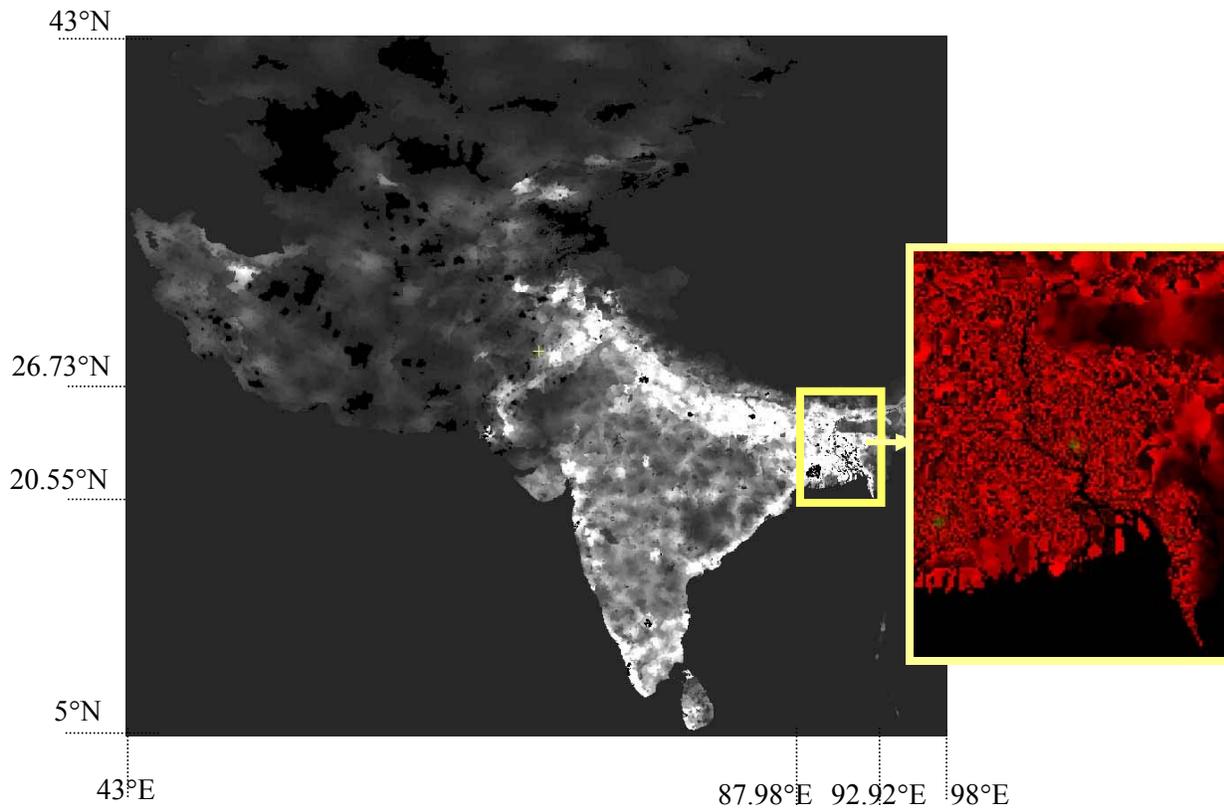


Fig. 21. Extraction of population density data from south-Asian country to Bangladesh with C++

B. Calculate the population per sq km: The population density (population per sq km) data set is available for the grid of $0.04667^\circ \times 0.04667^\circ$. This is equivalent to the area on earth of 5.189×5.189 sq km, using a conversion factor of 111.2 km/degree. This data set must be converted to population per sq km, i.e. from the grid of 5.189×5.189 sq km to the grid of 1×1 sq km.

As shown in Fig. 22, the given population density per sq km available in 5.189×5.189 sq km is superimposed with the area of 1×1 sq km. If the area of 1×1 sq km is completely in any area of 5.189×5.189 km, the population density per sq km in the area of 1×1 sq km will be the same as that in the area of 5.189×5.189 km (see the areas that contain p_1 , p_2 , p_3 and p_4 in Fig. 22). On the other hand, if the area of 1×1 sq km falls onto more than one of the given 5.189×5.189 sq km areas (see the dotted squares in Fig. 22), the resulting population density per sq km of this 1×1 sq km area is the proportion of the population density and the areas, onto which this 1×1 sq km area falls. For example, the dotted square in the middle of the figure falls onto the 4 areas that have population density of p_1 , p_2 , p_3 and p_4 , respectively. Thus, the population density in this square is a function of p_1 , p_2 , p_3 and p_4 .

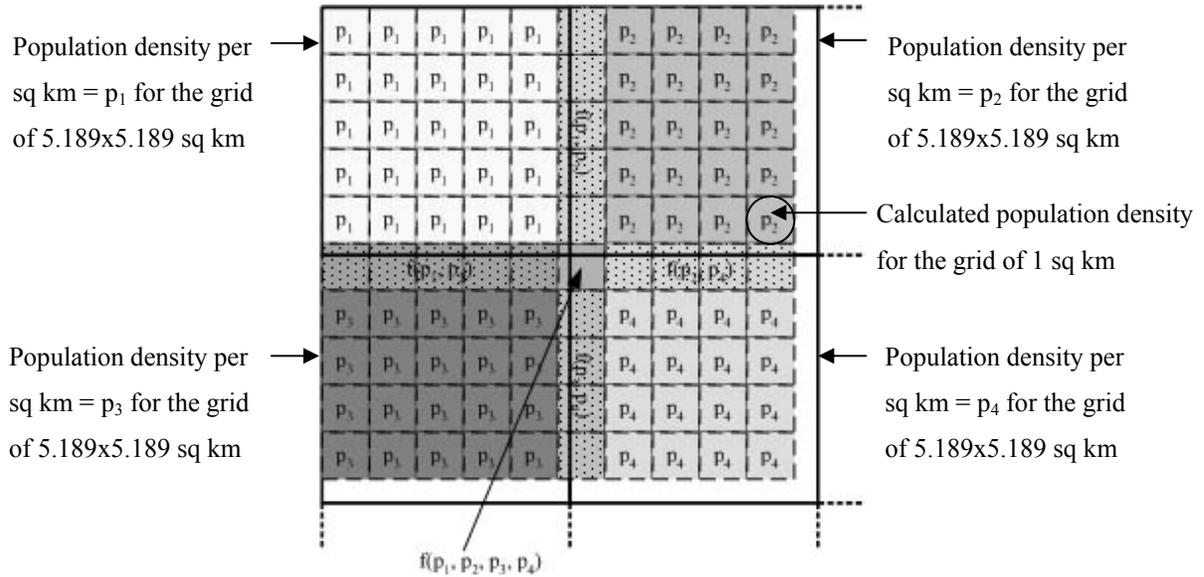


Fig. 22. Calculation of population density from the grid of 5.189x5.189 sq km to the grid of 1x1 sq km

C. *Select an area of interest:* The developed computer model can display the political boundary so that the user can select an area of interest. As shown in Fig. 23, the selected area is in the south-eastern part of Bangladesh. The selected area is given a value of 1; and the unselected area is given a value of 0. Once the 0-1 matrix of area of interest is logically multiplied (AND) with the extracted population density from 7.2A and 7.2B, this yields the population density per sq km in the area of interest, i.e. P_{cd} in eq. 3-12.

D. *Produce a matrix $[A_{i,cd}]$ for each base station i :* Using the information of the technology coverage distance, source nodes, and destination nodes, a coverage matrix must be produced according to section 3.2E for each base station i . An element of this matrix is $A_{i,cd}$ in eq. 3-14 and eq. 3-15.

E. *Construct a network of railways and highways:* The network of railways and highways is constructed based on the given GIS data. The extracted information includes arc ID, tail ID, head ID, and length or cost of laying optical fiber along each arc ij (δ_{ij} in eq. 3-10), as discussed in section 3.2C.

F. *Specify Goal:* The main focus of this model is to cover a specific percent of the total population in the area of interest. In this study, three case studies are conducted, namely, to

provide IT services to at least 50%, 70%, and 90% of the total population in Chittagong and Chittagong Hill Tracts. This parameter is χ in eq. 3-12.

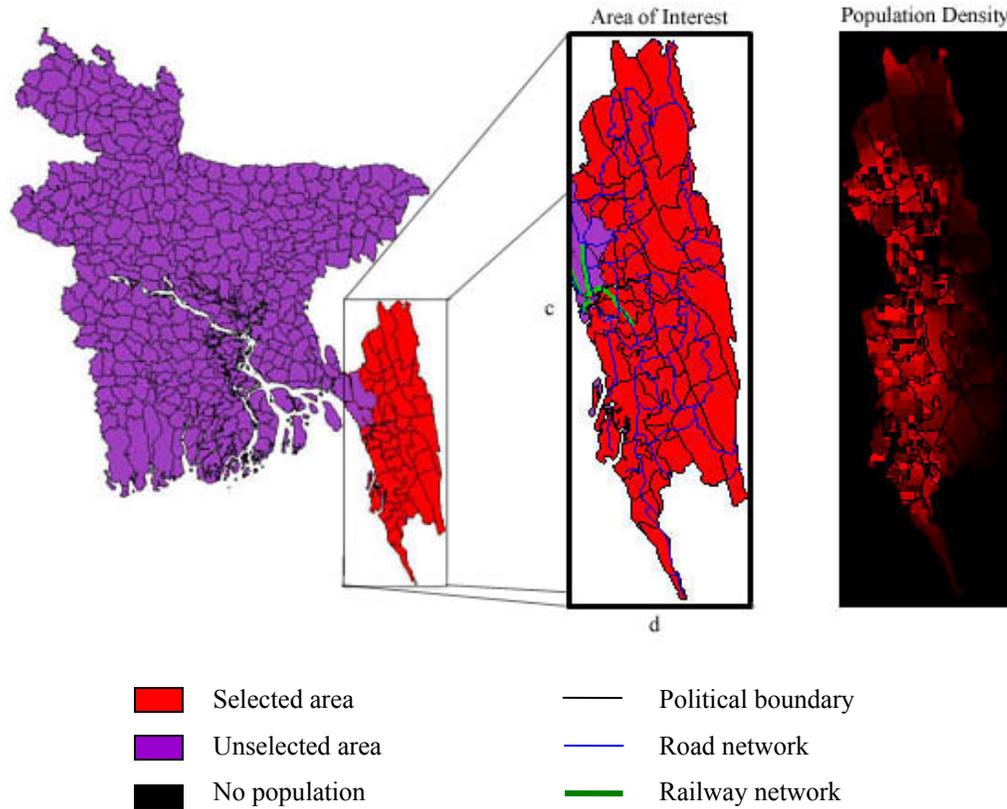


Fig. 23. Political boundary and selected areas

7.3 Case Studies of Bangladesh

To produce the Telecom-and-Internet access map for Chittagong and Chittagong Hill Tracts and to illustrate the usefulness of the model as a tool for preliminary site selection, the model is run using inputs and assumptions stated above. The problem has 24,568 variables and 45,136 linear constraints, and run on PIII, 900MHz, 512MB RAM. Fig. 24, 25 and 26 show the outputs of the model, which are Telecom-and-Internet access maps for providing Internet service to at least 50%, 70% and 90% of the total population in Chittagong and Chittagong Hill Tracts, respectively.

Case 1: 50 percent coverage

To provide Internet service to at least 50% of the total population in this area, only one 802.16 base station with 35-km coverage is selected to install at the location b (92.0525° , 22.1992°), as shown in Fig. 24. The map suggests optical fiber be extended from the PSTN location a (91.9320° , 22.3560°) to this location. The total length of the optical fiber cable is 23.2 km. This route is represented by the white line, as shown in Fig. 24, and the latitude and longitude of this route are summarized in Table C-1.

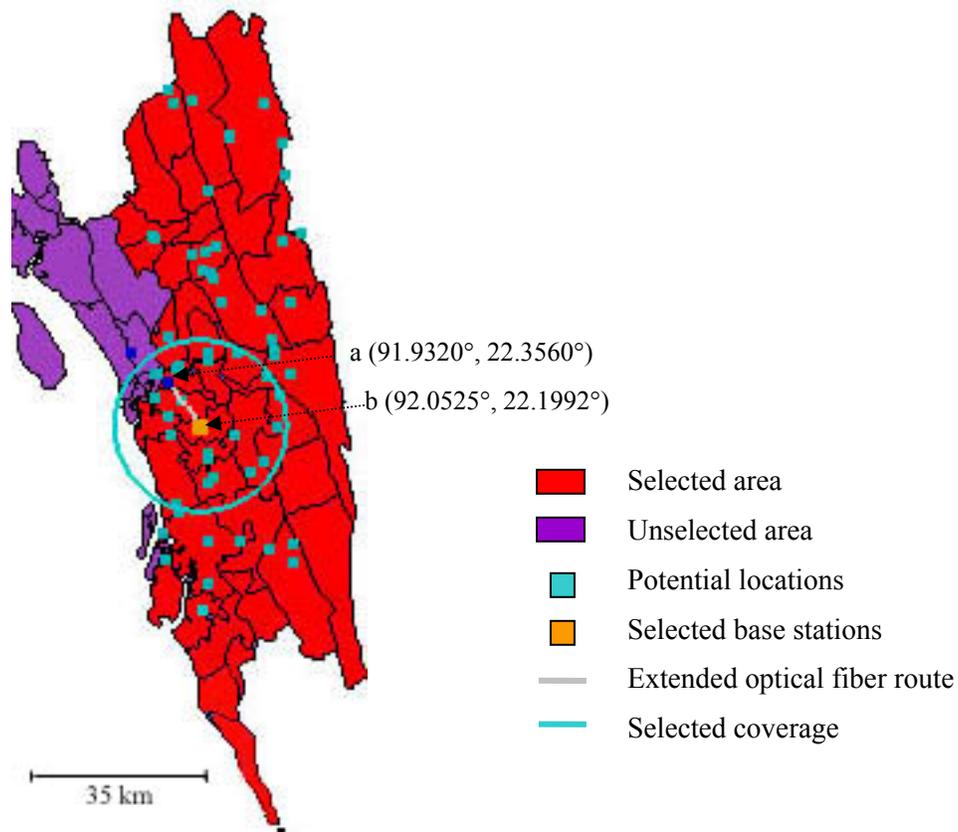


Fig. 24. A Telecom-and-Internet access map for 50% Internet coverage

According to this selection, the total population covered is 50.9 percent. Total equipment and installation cost is \$181,762, which includes the cost of one base station, one tower, and optical fiber extension. The cost of one base station and one tower is \$86,984. The rest is the cost of optical fiber extension for 23.2 km, which is \$94,778. Considering a VSAT system that has investment cost of \$75,000 and monthly expense of \$8,000/mo, with an annual interest rate of 10 percent. According to Fig. 20, the cost of fiber extension for 23.2 km along the railway line is equivalent to the cost of setting up and operating VSAT for only 2.5 months. Thus, it is obvious that optical fiber extension is more economically feasible in this scenario.

Case 2: 70 percent coverage

Fig. 25 indicates the Telecom-and-Internet access map for providing Internet service to at least 70% of the population. The map suggests that two 802.16 base stations with 35-km coverage be installed at the locations a(91.9320°, 22.3560°) and b(92.0759°, 21.7744°). The first location is at the PSTN, and therefore no fiber extension is required. The second location has an existing microwave station, which eliminates the need for a tower. Optical fiber should be extended from the PSTN to the second base station, as represented by the white line in Fig. 25. The total population covered is 74.6 percent. Total cost of this scenario is \$674,013, which includes the cost of two base stations, one tower, and installing fiber cable for 129.1 km. The detailed latitude and longitude of this route are summarized in Table C-2.

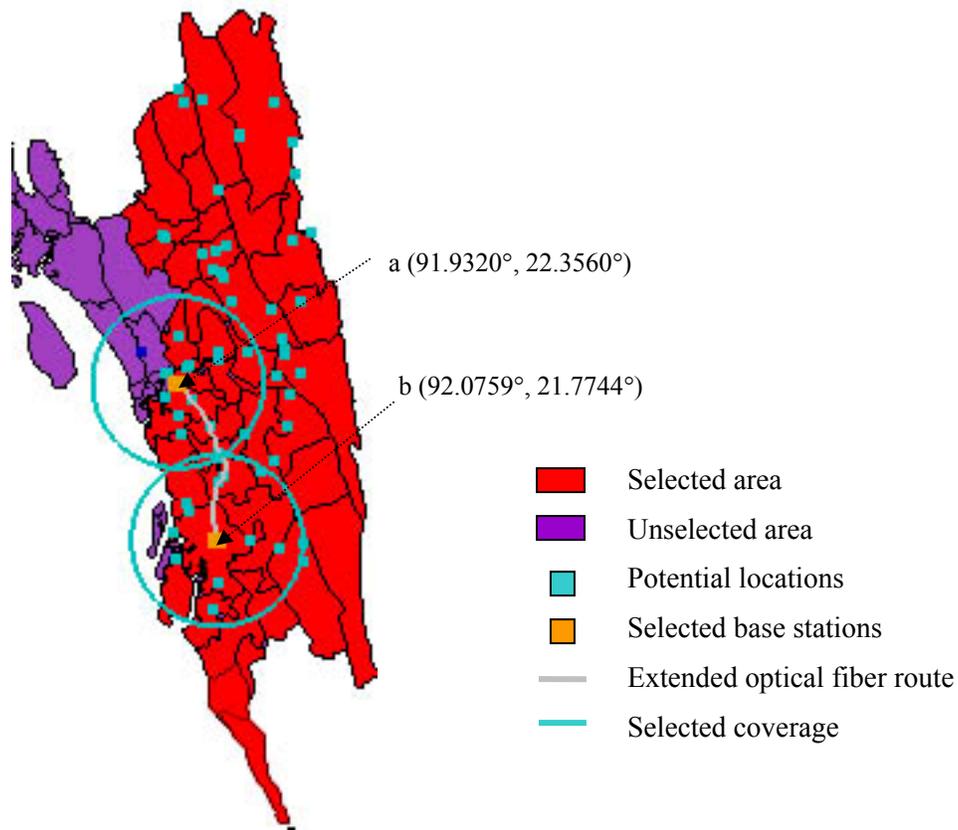


Fig. 25. A Telecom-and-Internet access map for 70% Internet coverage

In this scenario, the cost of two base stations and one tower is \$164,968, and the cost of extending optical fiber along railway and road networks for 76.4 km is \$509,045. This number is also equivalent to purchasing and operating a VSAT dish for about 6 years. However, since a microwave station exists at location (b), a VSAT system is not necessary for initial deployment at this location. The decision whether to continue using existing microwave station or to extend

optical fiber will ultimately depend on decision makers and the bandwidth requirement of the village.

Case 3: 90 percent coverage

Fig. 26 shows the Telecom-and-Internet access map for providing Internet access to at least 90% of the population in Chittagong and Chittagong Hill Tracts. The result suggests that only four wireless base stations are needed to provide Internet access to cover 90% of population.

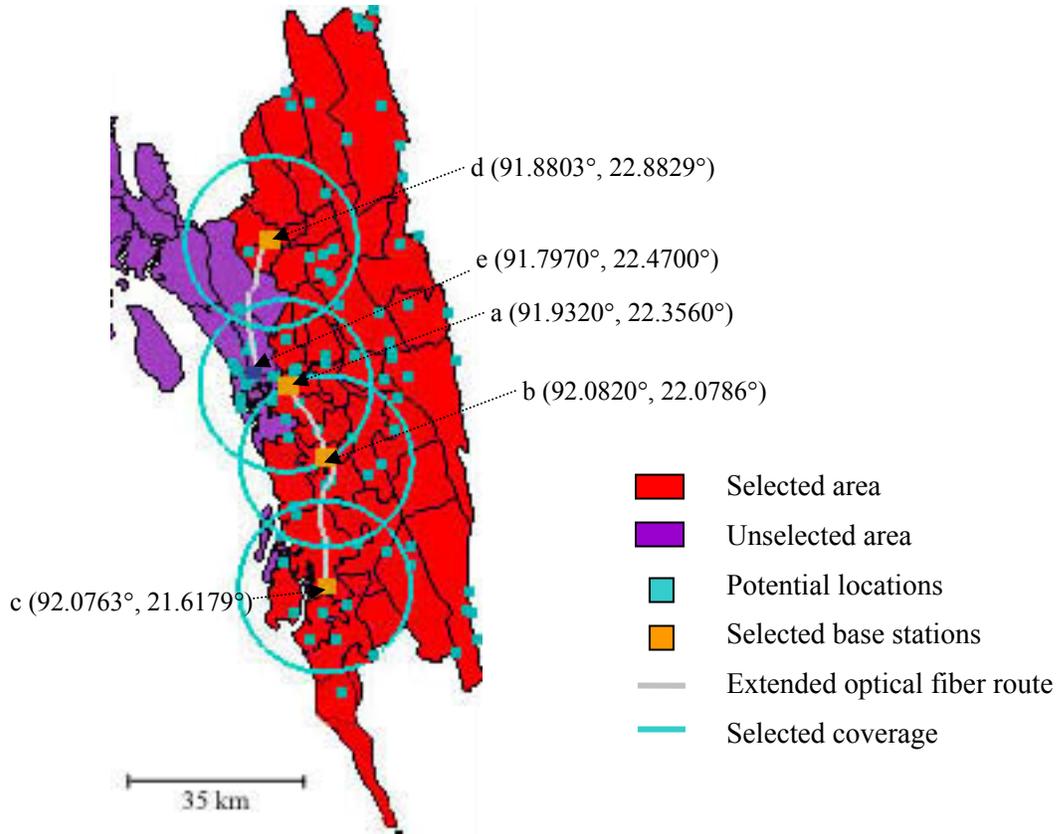


Fig. 26. A Telecom-and-Internet access map for 90% Internet coverage

The four base stations should be installed at the locations a(91.9320°, 22.3560°), b(92.0820°, 22.0786°), c(92.0763°, 21.6179°) and d(91.8803°, 22.8829°). The total population covered according to this scheme is 91.0 percent. Total cost is \$1,277,156, including the cost of four base stations, three towers and installing optical fiber for 170.1 km. The cost of four base stations and three towers is \$338,936; the rest is the cost of optical fiber extension, which is \$938,220.

The location (a) is at the PSTN so no fiber is needed at this location, but a wireless base station and a wireless tower are required. The location (b) has an existing microwave station, thus no

tower is required. The locations (c) and (d) do not have existing microwave infrastructures so setting up wireless towers is needed. Thus, the total of 4 base stations and 3 towers are required.

The map also suggests optical fiber cable be extended from the PSTN location (a) to the locations (b) and (c). The fiber length is 37.6 km (\$119,331) from location (a) to (b) and is 56.6 km (\$332,358) from the location (b) to (c). Similarly, the map suggests optical fiber cable be extended from the source location e(91.7970°, 22.4700°) to the location (d). The fiber length for this section is 75.9 km (\$414,533). The latitude and longitude of these routes are summarized in Table C-3.

In order to prioritize the investment decision for providing wide-area Internet access, locations with readily available infrastructures should be considered as the first priorities for setting up new base stations. In this case, the locations (a) and (b) are the locations that have access to the PSTN (via optical fiber and via microwave link, respectively). Therefore, these locations should be the first two locations to setup new base stations. Then, optical fiber should be eventually extended to the location (b) as the demand grows. For the locations (c) and (d), there are no existing infrastructures except the existing road network and rail network. These two locations should be considered as later priorities to provide Internet connection. For initial deployment, VSAT stations could be temporarily used for PSTN access. Then, optical fiber can still be extended to these locations at the least cost, according to the output from the developed telecom model.

7.4 Conclusions

In this chapter, the model to produce a Telecom-and-Internet access map is demonstrated. Three case studies are simulated to determine the least-cost telecom solutions to provide Internet service to 50%, 70% and 90% of the total population in the area of interest. Three Telecom-and-Internet access maps are produced, indicating locations for new base stations, wireless coverage areas, and routes to extend optical fiber. The results indicate that if 802.16 with the coverage of 35-km can be deployed in the area of Chittagong and Chittagong Hill Tracts, more than 90 percent of the population in this area can be brought on-line with as few as four newly installed base stations. To connect these new base stations to the national PSTN, optical fiber could be laid to these base stations along existing transportation infrastructures.

It is important to mention that total investment costs of the system are strictly based on the assumptions mentioned in section 3.1 and 7.1, and that the future refinement of the valid data sets will lead to a valid conclusion. That is, actual investment costs may differ from what the model suggests, according to actual site locations, and the decision to install VSAT or use existing

microwave links instead of extending optical fiber for PSTN access. Once the Telecom-and-Internet access map is obtained, a more in-depth study and site surveys must be conducted in order to determine actual site locations and actual investment costs.

Chapter 8

Power Solutions for Telecenter Kiosks

This chapter implements a power optimization model to design optimum configurations of power supply systems for telecenter kiosks. Demand and supply assumptions are summarized in section 8.1. Scenario description is presented in section 8.2. Power solutions for high-demand and low-demand telecenters are summarized in sections 8.3 and 8.4, respectively. These power solutions result from the implementation of the power optimization model developed in Chapter 4. The last section verifies those configurations using the dispatch algorithm developed in Chapter 5.

8.1 Demand and Supply Assumptions

A. Demand for telecenter kiosks: This research classifies a center for telecommunications or a Telecenter kiosk into two types: a high-demand telecenter, and a low-demand telecenter. Power consumption and operating time of equipment in the kiosks are summarized in Table 5.

Table 5. Power consumptions for various end-use appliances

Appliances	Power (W)	Quantity in telecenters		Operating time
		low- demand	High- demand	
Computer and webcam	150	1	5	8am-4pm (M-F), 8am-12pm (Sat)
Fax/printer	10	1	1	24 hours/day (M-S)
TV	20	1	2	6am-8pm (M-F), 6am-12pm (Sat)
Radio	8	1	2	6am-8pm (M-F), 6am-12pm (Sat)
Fluorescent lamp	8	2	5	1 light for 24 hours/day (M-S); the rests 6am-8pm (M-F), 6am-12pm (Sat)
Ceiling fan	8	1	3	8am-4pm (M-F), 8am-12pm (Sat)
Cordless phone	3	1	5	24 hours/day (M-S)
802.16 CPE & router	30	1	1	24 hours/day (M-S)

Each telecenter has one 802.16 customer premise equipment (CPE), and various end-user appliances (i.e. computers, web cameras, TVs, radios, etc). It is assumed that the low-demand telecenter will accommodate the following: 1 computer; 1 web camera; 1 fax/printer; 1 TV; 1 radio; 2 fluorescent lamps; 1 ceiling fan; 1 cordless phone and 1 CPE. In contrast, the high-demand telecenter accommodations will include: 5 computers; 5 web cameras; 1 fax/printer; 2 TV; 2 radios; 5 fluorescent lamps; 3 ceiling fans; 5 cordless phones and 1 CPE.

Fig. 27 illustrates demand curves for the high-demand and low-demand telecenters during typical weekdays. Peak demands of the high-demand and low-demand telecenters are 925 watts and 257 watts, respectively. Off-peak demands of both telecenters are 51 watts.

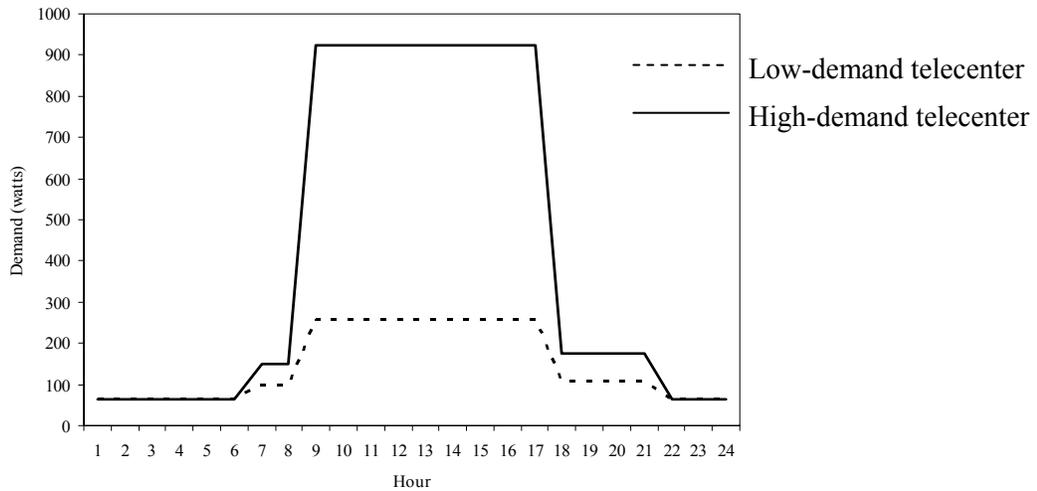


Fig. 27. Demand for low-demand and high-demand telecenters on weekdays

It is assumed that both telecenters are operated only until noon on Saturdays, and closed on Sundays. The electricity demand when the telecenters are closed is flat and equal to the demand on Saturday evening at 51 watts. This amount of energy is used to provide lighting and other basic services.

B. Resource Availability: Due to the unavailability of solar and wind resources at the interested location in Bangladesh, historical hourly data from the Virginia Tech Solar Test Facility (VTSTF) was used as a proxy. The data used is for a 12 month period from January to December in 2001, and is summarized below.

Table 6. Solar insolation and wind speed from VTSTF as of 2001

Month	Average daily solar insolation (W/m ²)	Average daily wind speed (m/s)
January	2,446	1.90
February	3,349	1.88
March	3,865	2.13
April	5,359	1.85
May	5,364	1.22
June	6,429 (max)	1.19
July	5,842	1.18
August	5,651	1.06
September	4,879	0.98
October	4,175	1.71
November	3,222	1.30
December	2,103 (min)	1.80

C. Supply Assumptions: Power generating technologies in this case study include PV, WT, IC engines, PEM fuel cells, and battery storage. Table 7 summarizes unit sizes, investment costs, operation and maintenance (O&M) cost, and life time of each technology under consideration.

The unit cost of each technology is based on the price installed in the U.S. market as of July 2004. The cost of solar cell, which is \$8/watt, includes balance-of-system costs (except battery) and mounting expenses. The O&M costs are based on those of large machines [83]. The life of PEMFC is 10 years but it is assumed that the fuel cell stack must be replaced every 5 years and this replacement costs \$1,500/kW. It is important to mention that all equipment selected must be able to connect to the DC bus at the specified voltage, which is 24V. If any component produces 12V output, two of the same component must be connected in series to yield 24V output. For example, the PVX-340 battery produces 12V output. Thus, two 12V PVX-340T batteries must be connected in series to yield 24V output. The cost of PVX-340T used in the analysis must be two times the cost of one.

Table 7. Cost and specification of each generating technology at 24V (interest rate = 10%)

Components	Specifications (based on model#)	Unit costs	O&M costs	Lifetime	$C_j - S_j^c$ (24V system)
PV - 53W	53W Solar Panel	\$8/Watt	\$0.005/kWh	20 years	\$424
WT - 400W	Air403	\$2.5/Watt	\$0.005/kWh	10 years	\$1000
IC engine - 1kW	DNAC 50Hz	\$1500/kW	\$0.015/kWh	5 years	\$3,368.8
PEMFC - 1kW and fuel processor	IFC PC-29 PEMFC, and stream methane reformer	\$4,000/kW	\$0.01/kWh	10 years***	\$6,832.6
Battery - 33AH	PVX-340T	\$68.95	n/a	5 years	\$309.7

It is also assumed that the round-trip battery efficiency is 95%. The inverter efficiency is 76% (see appendix D for the determination of this value). Table 8 summarizes fuel consumption characteristics of IC engines and PEM fuel cells, based on linear curve fitting equation, shown in Fig. 10 and Fig. 11, respectively.

Table 8. Fuel consumption characteristics of IC engines and PEM fuel cells

	F_0	F_1	Fuel types	Fuel costs
IC engines (DNAC)	0.0667 l/h	0.27 l/kWh	Diesel oil	\$0.4821/liter
PEM fuel cells (IFC PC-29 PEMFC)	0 BTU/h	8424.8 BTU/kWh	Natural gas	\$9.759/MMBTU

D. Externality costs: This research considers the effect of environmental externalities, including NO_x , SO_2 and CO_2 , on the per kWh cost of power supply solutions. The total discounted cost of environmental externalities is calculated by multiplying the estimated discounted externality cost (\$/lb) by the emission factor of each power generating technology (lb/kWh), and by the total energy (kWh) generated by that technology within the planning horizon of 20 years. This relationship is shown in the third components of the objective function in eq. 4-11.

Externality costs and emission factors of an IC engine and a PEM fuel cell used in the case study are summarized in Table 9.

^c C_i is the discounted capital cost of technology i ; S_i is the discounted salvage value of technology i .

Table 9. Externality costs and emission factors for NO_x, SO₂, CO₂ and PM-10

Emission Type	Externality costs (\$/lb) [⁸⁴]	Emission factors for an IC engine (lb/MWh) [⁸⁵]	Emission factors for a PEM fuel cells (lb/MWh) [⁸⁴]
NO _x	4.2	21.8	0.03
SO ₂	0.99	0.454	0.006
CO ₂	0.014	1,432	1,078

8.2 Model Implementation

To implement the power optimization model presented in Chapter 4, the model is run utilizing the demand assumptions for both high-demand and low-demand telecenters. The economic and technical performance of each power generating technology used is as summarized in Table 7. Since the wind resource is extremely low at this site, i.e. less than 2 m/s for most of the time, this research will not include a wind turbine option in the analysis.

To illustrate the effect of variation in resource availability on the optimal configuration, two resource scenarios are considered, as shown in the table below. For the PV-BT system, the simulation is performed for four weeks or twenty-eight consecutive days. Solar insolation in June and December are used to represent high and low resource scenarios, respectively. For the IC-BT and FC-BT systems, the diesel oil and natural gas prices in the high resource scenario are the current market prices, whereas those in the low resource scenario are twice their current market prices.

Table 10. Resource description

Technology	High resource scenario (higher sunshine, average fuel costs)	Low resource scenario (lower sunshine, higher fuel costs)
PV-BT	Hourly solar insolation in June (Daily average 6,429W/m ²)	Hourly solar insolation in December (Daily average 2,103W/m ²)
IC-BT	Diesel price in Table 8 (\$0.4821/liter)	Twice of that in Table 8 (\$0.9642/liter)
FC-BT	Natural gas price in Table 8 (\$9.759/MMBTU)	Twice of that in Table 8 (\$19.518/MMBTU)

Lastly, the model is run at various reliability requirements, i.e. 100%, 90% and 80%. These numbers are equivalent to the expected energy not served (EENS) levels of 0%, 10% and 20%, respectively. Similar to the simulation of telecom model, the specification of the computer used is PIII 900MHz with 512MB RAM. The next section summarizes power solutions for a high-demand telecenter. Then, section 8.4 presents power solutions for a low-demand telecenter.

8.3 Power Solutions for a High-Demand Telecenter

The following table summarizes power solutions for a high-demand telecenter, which has the peak demand of 925 watts, when energy not served is not allowed (EENS = 0%). The effect of environmental externalities is included for IC engine and PEMFC options as shown in parentheses. Note that no externality cost is added to the LCCs of PV-BT systems since they produce no emissions during operation.

Table 11. Summary of power solutions for a high-demand telecenter when EENS = 0%

Scenario	High resource scenario (higher sunshine, average fuel costs)			Low resource scenario (lower sunshine, higher fuel costs)		
	Solutions	20-yr LCC	COE** (c/kWh)	Solutions	20-yr LCC	COE** (c/kWh)
PV-BT	2.332kW PV 549AH battery	\$24,444	41.6	6.625kW PV 2.74kAH battery	\$78,895	134.1
IC-BT	1kW IC 66AH battery	\$10,224 (\$18,680)*	17.4 (31.8)*	1kW IC 132AH battery	\$15,893 (\$24,285)*	27.0 (41.3)*
FC-BT	1kW FC 132AH battery	\$11,805 (\$13,253)*	20.1 (22.5)*	1kW FC 132AH battery	\$15,134 (\$16,528)*	25.7 (28.2)*

* Numbers in parentheses show costs with externalities; ** COE = cost of energy (c/kWh).

Fig. 28 and 29 illustrate the ranges of LCC per kWh of power solutions for the high-demand telecenter at various (EENS) levels, without externalities and with externalities, respectively. They show the possible variation in the LCC per kWh of energy generated from each technology. A lower bound of LCC per kWh of each technology is obtained by simulating with high resource availability, whereas an upper bound of LCC per kWh of each technology is obtained from simulating with low resource availability.

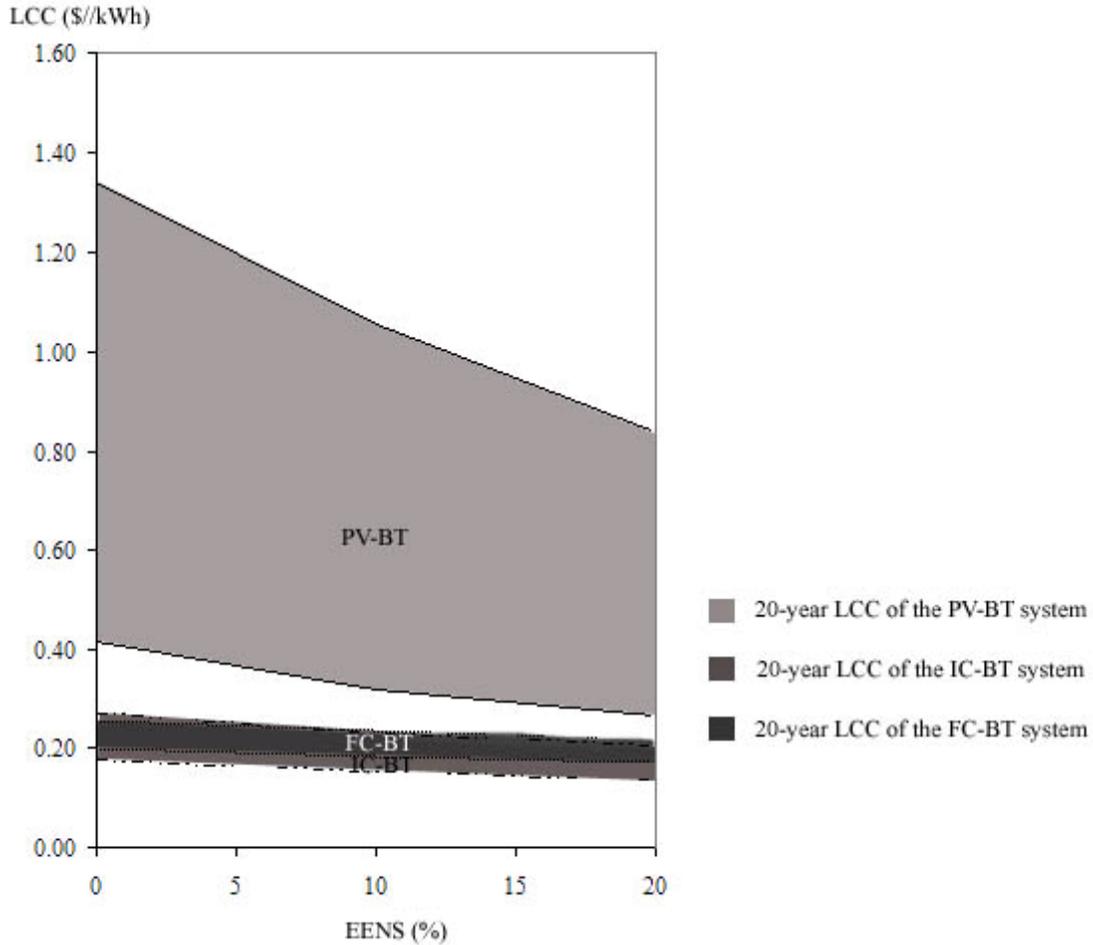


Fig. 28. Summary of 20-year LCC per kWh at various EENS levels for a high-demand telecenter without externalities

The following items highlight key ideas of power solutions for the high-demand telecenter.

- *When no externalities are considered (see Fig. 28), the least-cost power solution is a 1 kW IC engine with battery storage:* The 20-year LCC of the system is \$10,224 (17.4 c/kWh) when EENS is not allowed, and is \$7,839 (13.3 c/kWh) when EENS is allowed at 20%.
- *The 20-year LCC per kWh of the system with an IC engine depends greatly on fuel price:* When diesel oil price varies from its base price to twice that much, the LCC per kWh increases from 17.4 c/kWh to 27.0 c/kWh (EENS=0). The larger battery size should be used when diesel price increases to cut down fuel cost. However, if unserved energy is allowed at 20%, a battery is not necessary.

- *A PEM fuel cell can be seen as a future competitor of an IC engine since the LCC per kWh of the PEM fuel cell is comparable to that of the IC: The 20-year LCC of PEM fuel cells is \$11,805 (20.1 c/kWh) when EENS is not allowed.*
- *The 20-year LCC per kWh of the system with a PEM fuel cell is less sensitive to fuel price than the system with an IC engine: When the natural gas price varies from its base price to twice as much, the LCC per kWh increases slightly from 20.1 c/kWh to 25.7 c/kWh (EENS=0). This is because: (i) the investment cost of a FC is higher than that of an IC engine; (ii) the natural gas price is low compared to diesel oil price; and (iii) a PEMFC is more efficient than an IC engine.*

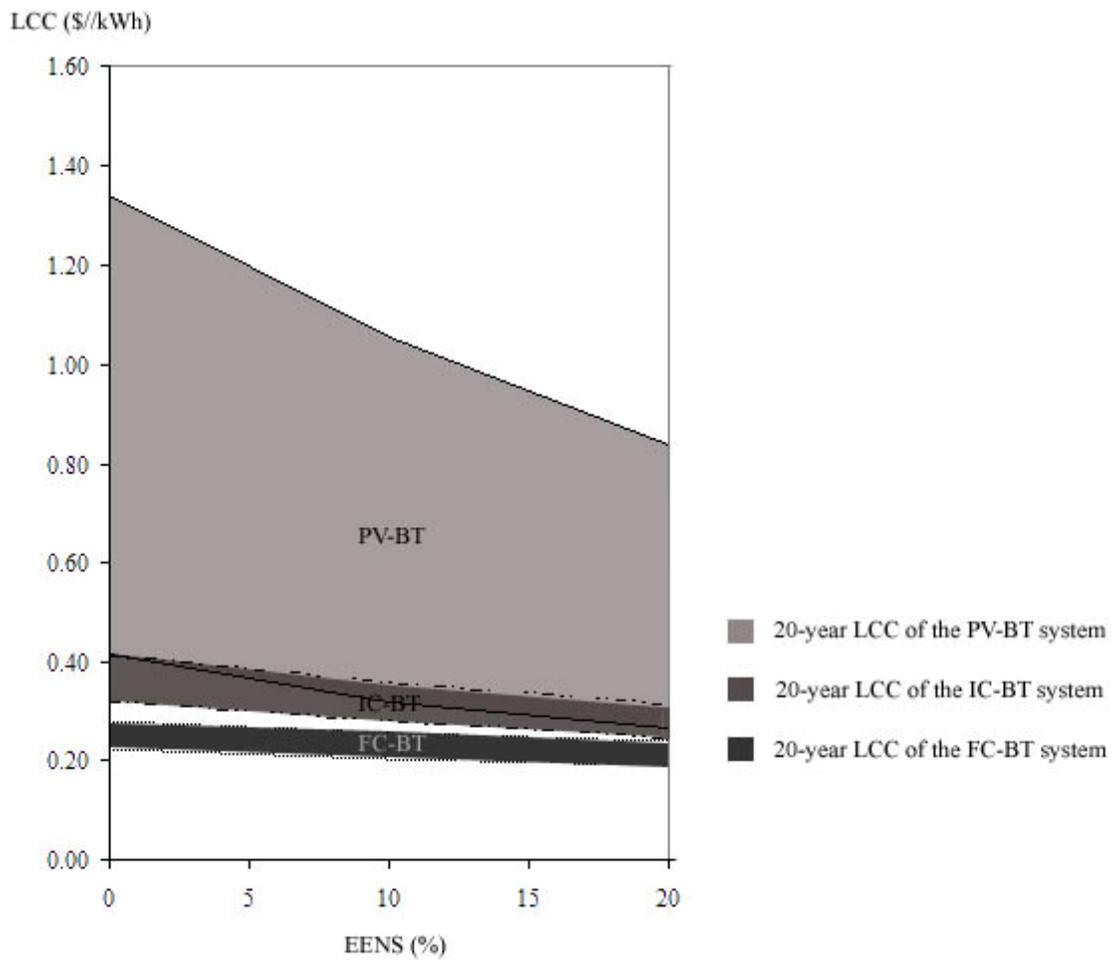


Fig. 29. Summary of 20-year LCC per kWh at various EENS levels for a high-demand telecenter with externalities

- *The total LCC per kWh of a PEM fuel cell becomes lower than that of an IC engine when environmental externalities are included (see Fig. 29):* The result indicates that the additional cost due to externalities is 11.0-15.9 c/kWh for IC engines, and is 1.98-2.46 c/kWh for PEM fuel cells. Since PV systems do not produce NO_x, SO₂, and CO₂ during operation, their costs remain the same with or without externalities considered.
- *If no fossil fuels are available in the village, PV-BT system is the least-cost solution:* if a certain portion of demand is allowed to not be served, the total system LCC of PV systems could decrease tremendously. The unmet energy could be met by an IC engine, if needed.
- *The design of PV-BT system also depends greatly on resource availability:* In the low solar insolation month, both PV panels and battery storage must be sized larger than those in the high solar insolation month, in order to cover the same demand. The estimated LCC per kWh of the PV-BT system thus increases from 41.6 to 134.1 c/kWh (EENS=0).

8.3 Power Solutions for a Low-Demand Telecenter

The following table summarizes power solutions for the low-demand telecenter designed using high resource data and low resource data, when energy not served is not allowed. Similar to cases of the high-demand telecenter, the effect of environmental externalities is included only for IC engine and PEMFC options as PV-BT systems produce no emissions during operation.

Table 12. Summary of power solutions for a high-demand telecenter when EENS = 0%

Scenario	High resource scenario (higher sunshine, average fuel costs)			Low resource scenario (lower sunshine, higher fuel costs)		
	Solutions	20-yr LCC	COE** (c/kWh)	Solutions	20-yr LCC	COE** (c/kWh)
PV-BT	848W PV 231AH battery	\$9,029	41.0	2.544kW PV 990AH battery	\$29,716	134.9
IC-BT	1kW IC 66AH battery	\$7,047 (\$10,547)*	32.0 (47.9)*	1kW IC 99AH battery	\$10,025 (\$13,335)*	45.5 (60.6)*
FC-BT	1kW FC 66AH battery	\$8,838 (\$9,318)*	40.1 (42.3)*	1kW FC 66AH battery	\$10,003 (\$10,526)*	45.4 (47.8)*

* Numbers in parentheses show costs with externalities; ** COE = cost of energy (c/kWh).

Fig. 30 and 31 illustrate the ranges of LCC per kWh of power solutions for the low-demand telecenter at various expected energy not served (EENS) levels, without externalities and with externalities, respectively. They show the possible variation in the LCC per kWh of energy generated from each distributed generation technology, when the high resource scenario is considered as a lower bound of LCC/kWh, and the low resource scenario is considered as an upper bound of LCC/kWh.

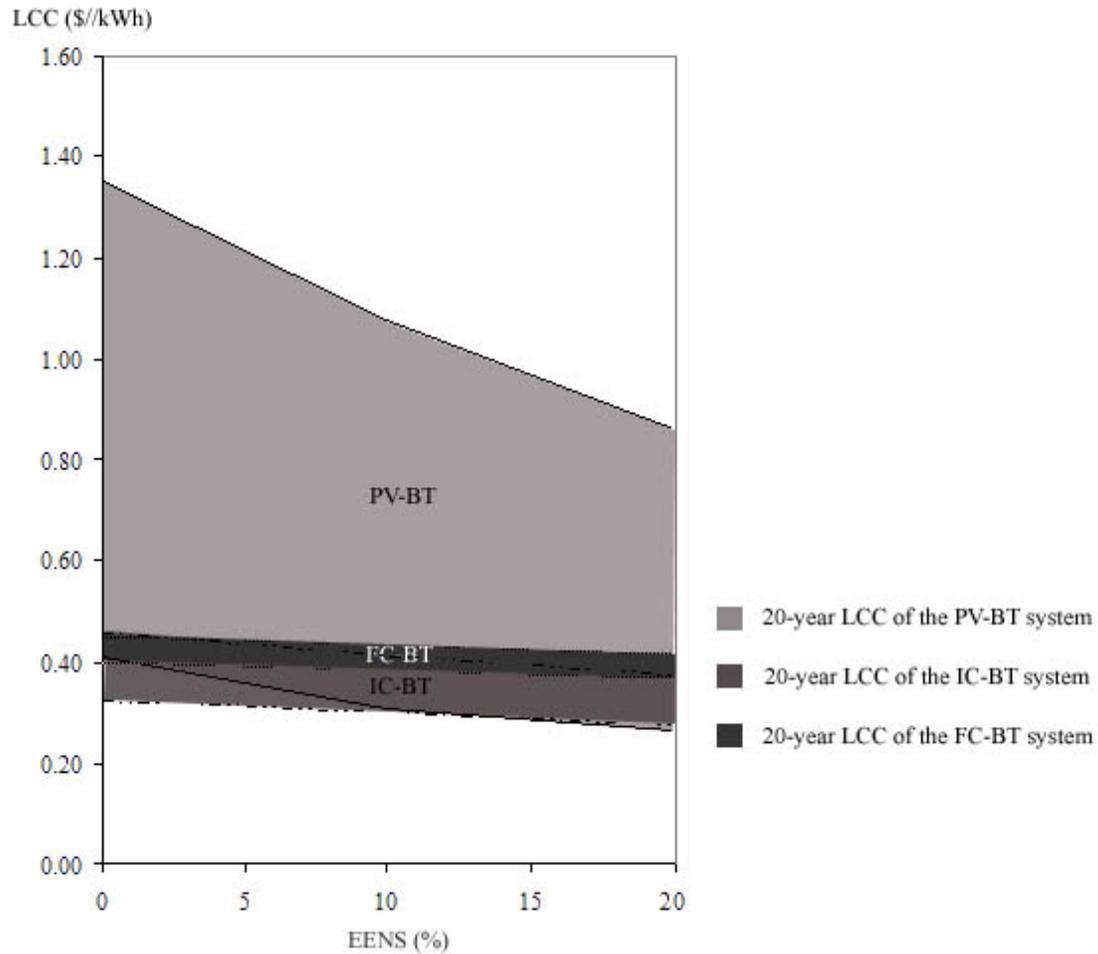


Fig. 30. Summary of 20-year LCC per kWh at various EENS levels for a low-demand telecenter without externalities

The following items highlight key ideas of power solutions for the low-demand telecenter.

- *The 20-year LCC per kWh of an IC engine and a PEM fuel cell increases tremendously in the low-demand telecenter, as opposed to the cases in the high-demand telecenter:* For example, the LCC per kWh of an IC engine is 32.0 – 45.5 c/kWh in the low-demand telecenter, whereas it is

17.4 – 27.0 c/kWh in the high-demand telecenter (when EENS=0). The LCC per kWh of PEM fuel cells is 40.1 – 45.4 c/kWh in the low-demand telecenter, whereas it is 20.1 – 25.7 c/kWh in the high-demand telecenter (when EENS=0).

- *In contrast, the 20-year LCC per kWh of PV systems is relatively the same for both high-demand and low-demand telecenters: The LCC per kWh of PV systems is 41.0 – 134.9 c/kWh in the low-demand telecenter, whereas it is 41.6 – 134.1 c/kWh in the high-demand telecenter (when EENS=0). This is due to the fact that the PV array is modular and can be added or removed according to the increase or decrease demand.*

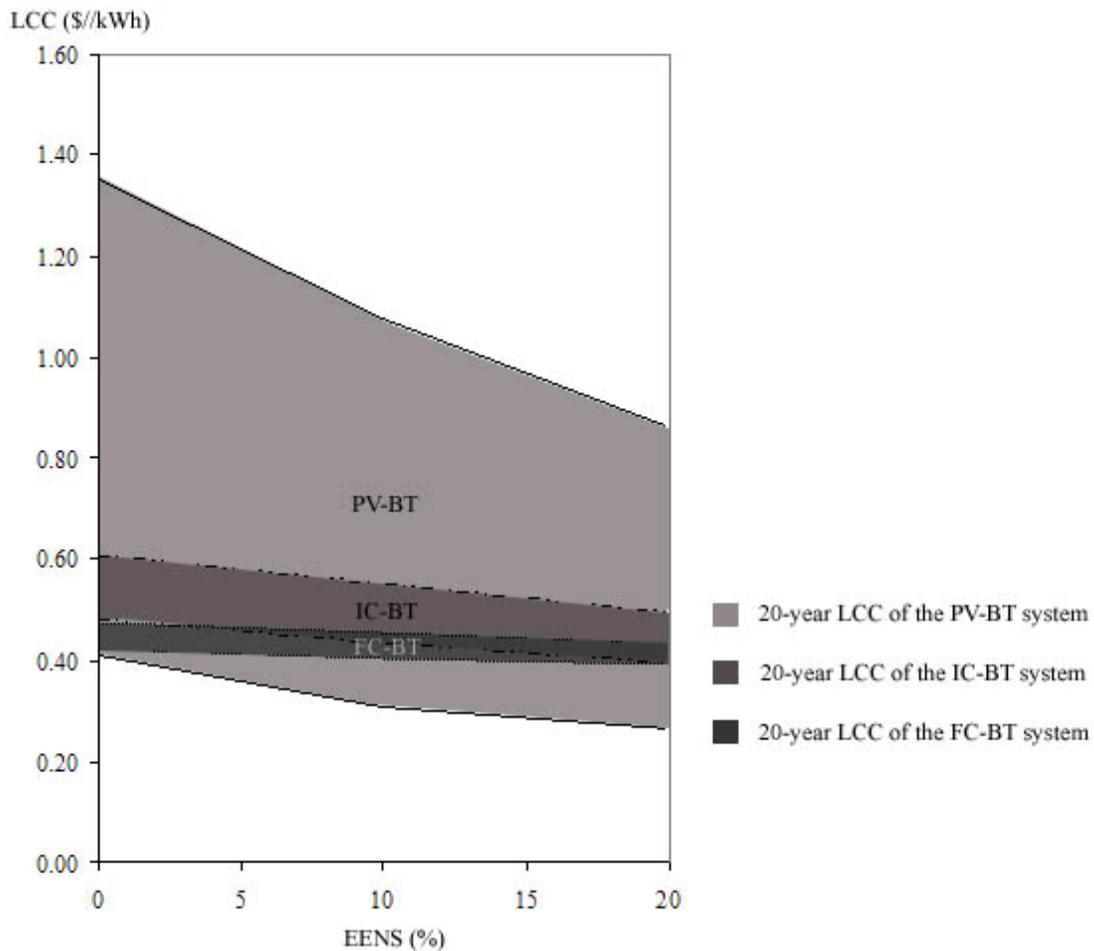


Fig. 31. Summary of 20-year LCC per kWh at various EENS levels for a low-demand telecenter with externalities

- *With environmental externalities included (see Fig. 31):* The additional cost due to externalities is about 12.2-15.9 c/kWh for IC engines, and is approximately 1.87-2.37 c/kWh for PEM fuel cells (EENS=0) for the low-demand telecenter.

8.4 Verification of Results

The purpose of this section is to determine the unmet demand from simulating the operation of the designed configurations based on the dispatch methodology discussed in Chapter 5. Table 13 shows the (simulated) monthly unmet demand for the PV-BT systems, designed using highest solar insolation month and lowest solar insolation month. Only the PV-BT systems are considered in the simulation because IC engines or PEMFCs can be controlled to start or stop. Thus, as long as fossil fuels are available in the village, the amount of unmet energy can be controlled to meet the reliability requirement.

Table 13. Verification of unmet demand of PV-BT systems

Month	High-demand telecenter		Low-demand telecenter	
	EENS (%) w/ 2.332kW PV 549AH BT (High resource)	EENS (%) w/ 6.625kW PV 2.74kAH BT (Low resource)	EENS (%) w/ 848W PV 231AH BT (High resource)	EENS (%) w/ 2.544kW PV 990AH BT (Low resource)
	January	41.28%	0%	41.31%
February	26.76%	0%	27.08%	0%
March	23.10%	0%	22.53%	0%
April	9.23%	0%	8.22%	0%
May	6.54%	0%	5.82%	0%
June	0%	0%	0%	0%
July	1.08%	0%	0.8%	0%
August	0.72%	0%	0.46%	0%
September	4.69%	0%	3.73%	0%
October	14.03%	0%	13.61%	0%
November	19.01%	0%	19.36%	0%
December	45.42%	0%	45.1%	0%

The results indicate that the PV-BT systems that are designed to cover the lowest solar insolation month can be used to supply energy for the whole year without unmet demand. In contrast, the PV-BT systems that are designed to cover the highest solar insolation month (unmet demand in Jun = 0%) cannot sustain the demand in the other months that have lower solar insolation.

8.5 Conclusions

This chapter presents the optimal configurations of various supply options for the hypothetical high-demand and a low-demand telecenters, using the methodology developed in Chapter 4. The estimated 20-year life cycle cost of each supply option is summarized as a range of possible cost per kWh according to the variation in locally available resource. For each solution, a spreadsheet is created to cross check the validity of the resulting system life cycle costs. The optimization results indicate that the least-cost power supply option for both types of telecenters is to use a 1-kW IC engine with battery storage. A PEM fuel cell becomes attractive compared to an IC engine if emissions are of major concern. PV systems appear to be more cost-effective to use in a low-demand telecenter than IC engines or PEM fuel cells and when externality costs are included.

Lastly, it is important to note that the data sets used are assumed in order to demonstrate the use of the model. Once the actual kiosk location (which will determine resource availability, O&M cost, fuel cost, etc.) is known and the appliances in the kiosk are determined, valid data sets can be used to get more accurate results.

Chapter 9

Conclusions and Recommendations

9.1 Conclusions

Since the access to digital services can potentially enhance the quality of lives of people in remote areas, the main focus of this dissertation is to develop a methodology with analytical tools that analyze plans for the least-cost Internet and power access to a remote area. The model is intended to be used as a screening tool for planners, policy makers and service providers to analyze possible alternatives. Once the technology and protocols are chosen, in-depth design studies can be conducted by vendors for system deployment.

Regarding the Internet access, the dissertation demonstrates a tool to produce a Telecom-and-Internet access map of a region or a small country. The Telecom-and-Internet access map illustrates the combination of technologies and their locations to provide wide-area Internet access to a majority of the population at the least possible cost. The model utilizes GIS information about existing infrastructures in an area of interest to evaluate the potential of extending the reach of the Internet access to last-mile areas at the lowest cost. In addition to telecommunication infrastructure, electric power - which is an absolute prerequisite to the use of the Internet - must be provided to make the Internet possible. The model also helps in the design of an optimum hybrid energy system to provide local power supply. Decision criteria include interdependencies among locally available resources, demand and supply characteristics, investment cost, environmental externality, technical performance, and system robustness.

In order to demonstrate the use of the model, an area of Chittagong and Chittagong Hill Tracts in southeastern Bangladesh was selected as a case study. Bangladesh was selected due to a low per capita number of telephone and Internet connections, yet with a national focus to build an ICT-driven nation in the near future. In addition, if it can be demonstrated that Internet and power can be provided in Chittagong and Chittagong Hill Tracts, which is one of the least developed areas and one of most difficult areas to access in Bangladesh, Internet and power can also be provided elsewhere. As the preliminary task, existing IT infrastructures of Bangladesh are reviewed to identify suitable telecommunication technologies for the country. The analysis indicates that Bangladesh has the building blocks of a nationwide IT infrastructure, i.e. optical fiber along railway lines, microwave links as existing backbone, and the future untapped bandwidth from the SEA-ME-WE4 submarine cable. However, this infrastructure is currently accessed primarily

from the major cities and towns. As a result, a large segment of the population is left without telephone and Internet connections.

To extend the reach of the Internet to the still inaccessible areas in Bangladesh, alternative telecom technologies are reviewed based on their performance, including data rate, coverage distance, and investment costs (based on 1000 lines). The evaluation of various last-mile access technologies (POTS, DSL, cable modem, WLL, MMDS, WWAN, 802.11, 802.16, and 802.20) indicates that 802.16 and WLL are potentially the most cost-effective for bridging the last-mile gap in the context of Bangladesh. The selection between these two alternatives will ultimately depend on the bandwidth requirement and the ability to pay for the service for local applications.

Once the promising telecommunication technologies are identified and necessary GIS datasets are gathered for the area of interest, Telecom-and-Internet access maps are generated using the developed model. Results indicate that at least 90% of the population in Chittagong and Chittagong Hill Tracts areas of Bangladesh can be served by installing as few as four wireless base stations. While optical fiber is the most effective long-term solution to connect these base stations to the national PSTN, fixed wireless or microwave radio links can be considered as interim solutions.

After identifying the most optimal IT technology, effective power supply configurations are determined for hypothetical kiosks using the developed power optimization model. Results indicate that an IC engine with battery storage generally provides the cheapest power solution if environmental costs are not included. When environmental externalities are considered, a PEM fuel cell with battery storage becomes more attractive than the IC engine in terms of its overall cost per kWh. The PV system with battery storage is currently very costly and only suitable to power a small kiosk in a location where emissions are of major concern. This research uses the months with the highest and lowest average daily solar insolutions to design stand-alone PV-battery systems. A yearly (12-month) simulation can be carried out, if longer computer simulation times are available.

In summary, this research presents the analytical tool to identify the alternatives to providing wide-area Internet access and a local power supply at the least cost. The application of the proposed model is demonstrated using the case study of a remote area in Bangladesh. The result indicates that a majority of the population in the least developed and the most difficult-to-access areas in Bangladesh can be served simply with only a few wireless base stations and a local power supply. Lastly, it is expected that the proposed methodology and the conducted case studies can be helpful in offering sustainable and affordable Internet and power solutions to

overcome the digital divide that limits the economic and social opportunities to a large segment of the world's population.

9.2 Suggestions for Variations in Model Implementation and Future Research

For the telecom optimization model, selecting potential base station locations from an actual site survey is one of the most important factors. The market price information on the costs of equipment, towers, site installation, interconnection to the PSTN, as well as the cost of electricity at the base station should be used for each potential base station location. If the potential base station location is not electrified, the cost information on electricity infrastructure required at the base station can be determined by running the power optimization model using the demand and available energy resources at the base station location. This makes it possible for decoupling the telecom and power optimization problems to give valid solutions.

For the power optimization model, the costs of generators including fuel and delivery, and operation and maintenance (O&M) costs should be used. As recommended earlier, the hourly solar insolation, and wind speed, if used, data should represent the typical meteorological year data sets. There is no restriction of how long the simulation period should be, but a longer simulation period will result in a longer simulation time.

In this research, the coverage matrix is assumed to be a perfect circle with the equation $(x-c)^2+(y-d)^2 = r^2$. This equation is used to assign the value of 0 or 1 to each cell (c, d) in each coverage matrix. The parameter r in this case is the coverage of the selected base station. Based on spatial data sets of terrain characteristics, interested researchers can alter the coverage matrix $[A_{i,cd}]$ to incorporate terrain information without changing the structure of the problem. The other possibility is to integrate the cost of feeder extension - as an alternative to distributed generation - into the objective function of the power optimization model. The model then can suggest whether the electric feeder should be extended to the kiosk location or the stand-alone energy system should be installed onsite.

Appendix – A

Electrolysis vs Reformer

One distinctive feature of PEM fuel cells is that, instead of using fossil fuels, hydrogen is used to produce electricity. Hydrogen can be produced from a variety of feedstock with a variety of process technologies. The two most popular methods are producing hydrogen from natural gas using a reformer, and deriving hydrogen from water with an electrolysis process.

With the reforming process, natural gas or other feedstock is used as a fuel input to the reformer. The reformer derives hydrogen from natural gas, which is instantaneously used to produce electricity by PEM fuel cells. With the electrolysis process, water atoms are broken into hydrogen and oxygen atoms in an electrolyzer, using excess electricity from renewable energy. The produced hydrogen is then compressed and stored in a hydrogen storage tank. Then, hydrogen is converted to electricity by PEM fuel cells. The inputs to this process are water and electricity, and the output is electricity and the by-products are just heat and water.

This section gives rationale to justify the use of a fuel reformer with PEM fuel cells, by comparing electrical efficiency of the process with its equivalent technology. Apparently, the reforming process is equivalent to the use of IC engines because their inputs are fossil fuels, and their outputs are electricity. The electrolysis process is, on the other hand, equivalent to the use of battery banks because, for both process, their inputs and outputs are electricity. Fig. A-1 and Fig. A-2 compare a reforming process vs. an IC engine; and an electrolysis process vs. battery storage, respectively. These processes are discussed below.

A. Comparison of electrical efficiency (PEM fuel cells with a reformer vs IC engines):

According to Fig. 10, the overall efficiency of an IC engine is roughly 15%-29%. Whereas, according to Fig. 11, the overall efficiency of a PEM fuel cell with a reformer is roughly 40-45%.

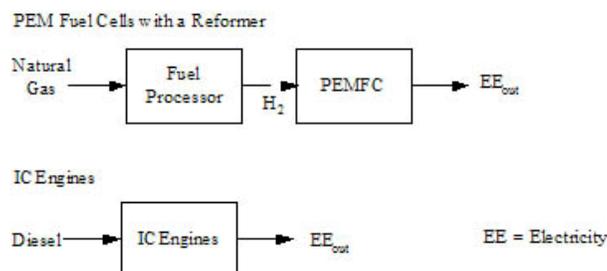


Fig. A-1. PEM fuel cells with a reformer vs. IC engines

It can therefore be concluded that, with respect to overall electrical efficiency, the performance of a PEM fuel cell with a reformer is better than that of an IC engine, as illustrated in Table A-1 (40%-45% as opposed to 15%-29%). While IC engines are mature and not much improvement can be added, fuel cell systems are emerging and their performance is expected to improve tremendously in the future. Thus, the PEM system with a reformer should be included in the analysis as a future competitor of IC engines.

Table A-1. Comparison of electrical efficiency of IC engine and PEMFC with reformer

	Technology	Overall efficiency	Efficiency definition
Input: fuel	IC engine	15-29%	$\eta_{IC\ engine}$
Output: electricity	PEM w/reformer	40-45%	$\eta_{reformer} \times \eta_{PEM\ fuel\ cells}$

B. Comparison of electrical efficiency (electrolysis process vs battery)

Typically, the round-trip electrical efficiency of a battery is roughly 95%. On the other hand, electrical efficiency for electrolysis process is defined here as a ratio of the total energy output to the total energy input. To produce 1 kg of hydrogen, the electrolyzer (based on Stuart IMET1000 model) requires 53.4 kWh of energy [86]. This number is equivalent to an efficiency of 73.7% (39.4/53.4) using the HHV of hydrogen (39.4 kWh/kg). The energy used to compress and store hydrogen at 200 bar is approximated at 8% and 5% of HHV of H₂, respectively [87]. Thus, the overall efficiency of compressor and hydrogen storage at 200 bar is 87%. Based on the IFC PC-29 model, the efficiency of PEM fuel cell stack alone ranges from 52% to 60%. These efficiency numbers are shown in Fig. A-2.

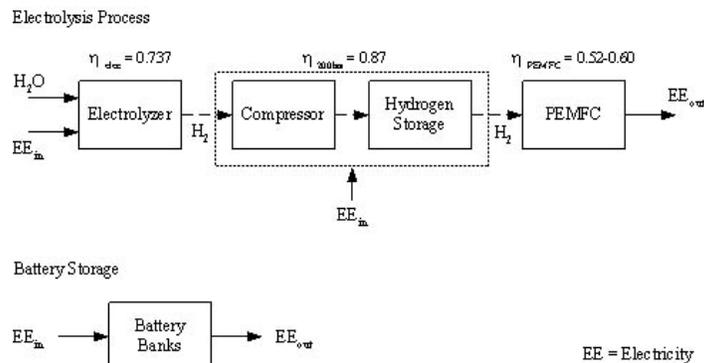


Fig. A-2. Electrolysis process vs battery

Thus, the overall electrical efficiency of electrolysis process is calculated as $\eta_{elec} \times \eta_{200bar} \times \eta_{PEMFC}$, which ranges from 33.3% to 38.4%, as shown in Table A-2.

Table A-2. Comparison of electrical efficiency of battery and electrolysis process

	Technology	Overall efficiency	Efficiency definition
Input: electricity	Battery	95%	$\eta_{battery}$
Output: electricity	Electrolysis	33.3 - 38.4%	$\eta_{elec} \times \eta_{200bar} \times \eta_{PEMFC}$

Therefore, it can be concluded that, unlike battery storage, the electrolysis process is not suitable for storage applications with respect to overall electrical efficiency (33.3%-38.4% as opposed to 95%). Thus, using the electrolysis process as a storage option is not considered in this dissertation. However, if the electricity to produce hydrogen comes from excess energy produced from renewable energy resources, such as PV and WT, renewable energy resources can be used more efficiently and no harmful emission is emitted. This salient feature makes electrolysis process recently gained remarkable interest for both urban and rural applications.

Appendix – B

Costs of Alternate Telecommunication Technologies

Table B-1: Comparison of investment costs of alternate telecom technologies in the context of Bangladesh

Cost based on 1,000 lines (\$)	Technologies			
	MMDS ⁴	WLL ⁵	802.16 ⁶	VSAT ⁷
Base station	224,500	73,480	77,984	75,000
Misc	13,350	13,350	13,350	4500
CPE	550,000	340,000	1,500,000	-
Annual fee	51,500	44,000	11,733	96,000
Cost of ownership	839,350	470,830	1,603,067	87,500

⁴ Prices are based on a quote from a U.S. company as of 2003; Base station equipment includes the base station, base station interface card, antenna, installation kit, lightning protector (for ¼ sector cell), router, hub, and accessories; Misc. includes PC, power backup for base station and O&M software. CPE includes indoor subscriber units, power pack adapter, patch antenna, and lightning protector.

⁵ Prices are a quote from an Indian company, reflecting Bangladesh FOB price, as of 2003; Base station equipment includes base station controller, PSTN interface module, interface card, omni directional antenna, installation kit, remote access switch, lightning protector, router, hub, and accessories, and network management software; Misc. are PC, power backup for base station and O&M software; CPE include subscriber units, power pack adapter, patch antenna, and lightning protector.

⁶ Prices are a quote from a Canadian company based in Bangladesh, as of 2004; Base station equipment is based on Libra5800 in point-to-multipoint system, including 5.8GHz 16dbi 90° sector antenna, cable, surge suppressor for 5.8GHz, and Ethernet surge suppressor; Misc. are PC, power backup for base station and O&M software; CPE includes radio, integrated antenna, and PanTilt kit.

⁷ Samudra E. Hauque, “Draft report on rural connectivity planning and related locally sustainable technologies”, ICT – assisted development project/World Bank P078458, February/March 2004.

Appendix – C

Optical Fiber Routes for the Three Case Studies

Table C-1: Optical fiber extension and potential base station locations for 50% coverage

arc ID	Tail Node	Head Node	Tail node		Head node		Length (km)	
			Latitude	Longitude	Latitude	Longitude		
D	417	1357	189	92.0454	22.2053	92.0525	22.1992	1.053062
	417	1357	189	92.0183	22.2529	92.0454	22.2053	6.162053
	417	1357	189	92.0042	22.2730	92.0183	22.2529	2.762144
	417	1357	189	91.9893	22.2860	92.0042	22.2730	2.224572
	417	1357	189	91.9813	22.2879	91.9893	22.2860	0.925035
	418	1359	1357	91.9807	22.2881	91.9813	22.2879	0.071151
	418	1359	1357	91.9753	22.2921	91.9807	22.2881	0.756013
	418	1359	1357	91.9733	22.2974	91.9753	22.2921	0.63729
	418	1359	1357	91.9637	22.3228	91.9733	22.2974	3.054784
	418	1359	1357	91.9351	22.3582	91.9637	22.3228	5.119825
S	418	1359	1357	91.9320	22.3560	91.9351	22.3582	0.427648
								23.19

S = source node; D = destination node

Table C-2: Optical fiber extension and potential base station locations for 70% coverage

arc ID	Tail Node	Head Node	Tail node		Head node		Length (km)	
			Latitude	Longitude	Latitude	Longitude		
D (b)	1630	1096	1364	92.081	21.7752	92.0759	21.7744	0.580766
	1622	1092	1096	92.0783	21.7945	92.081	21.7752	2.192394
	1622	1092	1096	92.0715	21.8214	92.0783	21.7945	3.121444
	1622	1092	1096	92.0637	21.8367	92.0715	21.8214	1.932022
	1622	1092	1096	92.0612	21.8469	92.0637	21.8367	1.18164
	1622	1092	1096	92.0614	21.8652	92.0612	21.8469	2.058873
	1622	1092	1096	92.0615	21.8931	92.0614	21.8652	3.13877
	1622	1092	1096	92.0668	21.9385	92.0615	21.8931	5.142185
	1622	1092	1096	92.0657	21.9614	92.0668	21.9385	2.579220
	1622	1092	1096	92.0682	21.9711	92.0657	21.9614	1.126911
	1622	1092	1096	92.0833	21.9850	92.0682	21.9711	2.308910
	1618	1091	1092	92.0891	21.9918	92.0833	21.9850	1.005476
	1618	1091	1092	92.0971	22.0066	92.0891	21.9918	1.892677
	1617	1362	1091	92.0968	22.0087	92.0971	22.0066	0.238649
	1617	1362	1091	92.1096	22.0365	92.0968	22.0087	3.443088
	1617	1362	1091	92.1120	22.0517	92.1096	22.0365	1.731185
	1617	1362	1091	92.1100	22.0613	92.1120	22.0517	1.103189
	1617	1362	1091	92.0965	22.0783	92.1100	22.0613	2.442183
	1617	1362	1091	92.0820	22.0786	92.0965	22.0783	1.631599
	1616	1088	1362	92.0807	22.0896	92.0820	22.0786	1.246112
	1616	1088	1362	92.0752	22.0965	92.0807	22.0896	0.992681
	1610	1087	1088	92.0790	22.1008	92.0752	22.0965	0.645578
	1609	1079	1087	92.0726	22.1177	92.0790	22.1008	2.033015
	1609	1079	1087	92.0700	22.1461	92.0726	22.1177	3.208361
	1609	1079	1087	92.0650	22.1556	92.0700	22.1461	1.207739
	1609	1079	1087	92.0529	22.1680	92.0650	22.1556	1.949109
	1609	1079	1087	92.0509	22.1873	92.0529	22.1680	2.182877

1609	1079	1087	92.0449	22.2004	92.0509	22.1873	1.620976	
1609	1079	1087	92.0325	22.2144	92.0449	22.2004	2.103961	
1609	1079	1087	92.0322	22.2150	92.0325	22.2144	0.075467	
1609	1079	1087	92.0236	22.2365	92.0322	22.2150	2.605073	
1609	1079	1087	92.0027	22.2723	92.0236	22.2365	4.663597	
1609	1079	1087	91.9816	22.2872	92.0027	22.2723	2.905943	
1597	1357	1079	91.9813	22.2879	91.9816	22.2872	0.085677	
419	1359	1357	91.9807	22.2881	91.9813	22.2879	0.071151	
419	1359	1357	91.9753	22.2921	91.9807	22.2881	0.756013	
419	1359	1357	91.9733	22.2974	91.9753	22.2921	0.637290	
419	1359	1357	91.9637	22.3228	91.9733	22.2974	3.054784	
419	1359	1357	91.9351	22.3582	91.9637	22.3228	5.119825	
S/D(a)	419	1359	1357	91.9320	22.3560	91.9351	22.3582	0.427648
								76.44

S = source node; D = destination node

Table C-3: Optical fiber extension and potential base station locations for 90% coverage

arc ID	Tail Node	Head Node	Tail node		Head node		Length (km)	
			Latitude	Longitude	Latitude	Longitude		
D (d)	1523	1001	923	91.8766	22.8809	91.8803	22.8829	0.473169
	1523	1001	923	91.8619	22.8666	91.8766	22.8809	2.307155
	1523	1001	923	91.859	22.8654	91.8619	22.8666	0.353078
	1523	1001	923	91.8551	22.8595	91.859	22.8654	0.795654
	1523	1001	923	91.8497	22.8514	91.8551	22.8595	0.095186
	1523	1001	923	91.8381	22.8385	91.8497	22.8514	1.951705
	1523	1001	923	91.8348	22.8322	91.8381	22.8385	0.800096
	1523	1001	923	91.8326	22.8235	91.8348	22.8322	1.009558
	1523	1001	923	91.8367	22.8013	91.8326	22.8235	2.539736
	1523	1001	923	91.8266	22.7701	91.8367	22.8013	3.689331
	1523	1001	923	91.8307	22.7465	91.8266	22.7701	2.694768
	1523	1001	923	91.8302	22.7416	91.8307	22.7465	0.554112
	1523	1001	923	91.8295	22.7305	91.8302	22.7416	0.746664
	1523	1001	923	91.8141	22.7106	91.8295	22.7350	3.24601
	1523	1001	923	91.8102	22.7096	91.8141	22.7106	0.452943
	1523	1001	923	91.8023	22.6986	91.8102	22.7096	1.523576
	1523	1001	923	91.7956	22.6826	91.8023	22.6986	1.951445
	1523	1001	923	91.7938	22.6748	91.7956	22.6826	0.900562
	1523	1001	923	91.7940	22.6573	91.7938	22.6748	1.968879
	1523	1001	923	91.7991	22.6437	91.7940	22.6573	1.634041
	1523	1001	923	91.8001	22.6265	91.7991	22.6437	1.938268
	1550	1029	1001	91.7999	22.6218	91.8001	22.6265	0.529229
	1550	1029	1001	91.7982	22.5755	91.7999	22.6218	5.21226
	1550	1029	1001	91.8061	22.5295	91.7982	22.5755	5.250762
	1550	1029	1001	91.8068	22.5128	91.8061	22.5295	1.8804
	1550	1029	1001	91.8133	22.4974	91.8068	22.5128	1.880501
	1555	1035	1029	91.8142	22.4875	91.8133	22.4974	1.118343
	1555	1035	1029	91.8172	22.4766	91.8142	22.4875	1.271847
	1582	1351	1035	91.8239	22.4487	91.8172	22.4766	3.227986
	1582	1351	1035	91.8275	22.4045	91.8239	22.4487	4.988966
	1582	1351	1035	91.8366	22.3774	91.8275	22.4045	3.216044
	1582	1351	1035	91.8367	22.3720	91.8366	22.3774	0.607604
	406	185	1351	91.8305	22.3670	91.8367	22.3720	0.896054
	406	185	1351	91.8245	22.3665	91.8305	22.3670	0.67734
	407	1358	185	91.8264	22.3727	91.8245	22.3665	0.729517
	407	1358	185	91.8260	22.3777	91.8264	22.3727	0.564297
	407	1358	185	91.8167	22.3938	91.8260	22.3777	2.091714
	407	1358	185	91.8108	22.4200	91.8167	22.3938	3.021311

	407	1358	185	91.8104	22.4260	91.8108	22.4200	0.676498
	407	1358	185	91.8132	22.4394	91.8104	22.4260	1.540059
S2	407	1358	185	91.7970	22.4700	91.8132	22.4394	3.895165
D(c)	1631	1364	1102	92.0757	21.6499	92.0763	21.6179	3.600633
	1631	1364	1102	92.0753	21.6688	92.0757	21.6499	2.126726
	1631	1364	1102	92.0779	21.6833	92.0753	21.6688	1.657267
	1631	1364	1102	92.0783	21.7038	92.0779	21.6833	2.306689
	1631	1364	1102	92.0830	21.7326	92.0783	21.7038	3.282861
	1631	1364	1102	92.0790	21.7561	92.0830	21.7326	2.681774
	1631	1364	1102	92.0759	21.7744	92.0790	21.7561	2.08808
	1630	1096	1364	92.0810	21.7752	92.0759	21.7744	0.574055
	1622	1092	1096	92.0783	21.7945	92.0810	21.7752	2.167059
	1622	1092	1096	92.0715	21.8214	92.0783	21.7945	3.085374
	1622	1092	1096	92.0637	21.8367	92.0715	21.8214	1.909696
	1622	1092	1096	92.0612	21.8469	92.0637	21.8367	1.167812
	1622	1092	1096	92.0614	21.8652	92.0612	21.8469	2.035082
	1622	1092	1096	92.0615	21.8931	92.0614	21.8652	3.10250
	1622	1092	1096	92.0668	21.9385	92.0615	21.8931	5.082765
	1622	1092	1096	92.0657	21.9614	92.0668	21.9385	2.549416
	1622	1092	1096	92.0682	21.9711	92.0657	21.9614	1.113889
	1622	1092	1096	92.0833	21.9850	92.0682	21.9711	2.282229
	1618	1091	1092	92.0891	21.9918	92.0833	21.9850	0.993857
	1618	1091	1092	92.0971	22.0066	92.0891	21.9918	1.870806
	1617	1362	1091	92.0968	22.0087	92.0971	22.0066	0.235891
	1617	1362	1091	92.1096	22.0365	92.0968	22.0087	3.403301
	1617	1362	1091	92.1120	22.0517	92.1096	22.0365	1.711180
	1617	1362	1091	92.1100	22.0613	92.1120	22.0517	1.090441
	1617	1362	1091	92.0965	22.0783	92.1100	22.0613	2.413962
D(b)	1617	1362	1091	92.0820	22.0786	92.0965	22.0783	1.621745
	1616	1088	1362	92.0807	22.0896	92.0820	22.0786	1.231713
	1616	1088	1362	92.0752	22.0965	92.0807	22.0896	0.981210
	1610	1087	1088	92.0790	22.1008	92.0752	22.0965	0.638117
	1609	1079	1087	92.0726	22.1177	92.0790	22.1008	2.009523
	1609	1079	1087	92.0700	22.1461	92.0726	22.1177	3.171287
	1609	1079	1087	92.0650	22.1556	92.0700	22.1461	1.193783
	1609	1079	1087	92.0529	22.1680	92.0650	22.1556	1.926586
	1609	1079	1087	92.0509	22.1873	92.0529	22.1680	2.157653
	1609	1079	1087	92.0449	22.2004	92.0509	22.1873	1.602245
	1609	1079	1087	92.0325	22.2144	92.0449	22.2004	2.079648
	1609	1079	1087	92.0322	22.2150	92.0325	22.2144	0.074595
	1609	1079	1087	92.0236	22.2365	92.0322	22.2150	2.574970
	1609	1079	1087	92.0027	22.2723	92.0236	22.2365	4.609706
	1609	1079	1087	91.9816	22.2872	92.0027	22.2723	2.872363
	1597	1357	1079	91.9813	22.2879	91.9816	22.2872	0.084687
	419	1359	1357	91.9807	22.2881	91.9813	22.2879	0.070329
	419	1359	1357	91.9753	22.2921	91.9807	22.2881	0.747277
	419	1359	1357	91.9733	22.2974	91.9753	22.2921	0.629926
	419	1359	1357	91.9637	22.3228	91.9733	22.2974	3.019484
	419	1359	1357	91.9351	22.3582	91.9637	22.3228	5.060663
S1/D(a)	419	1359	1357	91.9320	22.3560	91.9351	22.3582	0.422706

170.1

S = source node; D = destination node

Appendix – D

Determination of Inverter Efficiency

This section aims at determining the value of inverter efficiency to be used in eq. 4-17 to eq. 4-21. Generally, inverter efficiency varies according to its operating capacity factor, that is, the efficiency is low at low capacity factor and higher at higher capacity factor as shown in Fig. D-1.

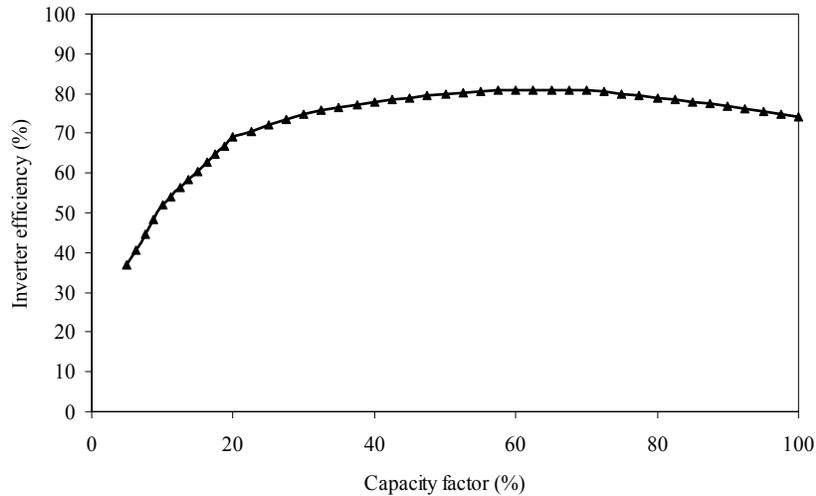


Fig. D-1. Inverter efficiency [⁸⁸]

The effect of using this inverter efficiency curve on PV output is shown in Fig. D-2. The figure shows the measured output data of PV module M55 from VTSTF (Virginia Tech Test Facility), Blacksburg, VA. Notice that the measured AC power output of PV array (ACWM55) is lower than its measured DC power output (ADCPM55), and is zero when the DC power output is low.

From Fig. D-2, M55POA is the measured module M55 plane radiation (Watt/m^2); ADCPM55 is the measured module M55 average array DC power (Watt); ACWM55 is the measured module M55 AC output power (Watt). The modeled PV output is the calculated PV output, based on eq. 4-17 using M55POA as input solar insolation (E_{ysi}), E_0 of $1000 \text{ W}/\text{m}^2$, T_c of $0.049\%/^{\circ}\text{C}$, and the inverter efficiency as shown in Fig. D-1. Fig. D-2 illustrates how close the modeled PV output power using eq. 4-17 to the measured module M55 AC output power (ACWM55).

However, the relationship of inverter efficiency and capacity factor is non-linear and cannot be taken into account in the developed linear-optimization model. This research, hence, assumed that inverter efficiency is a constant value.

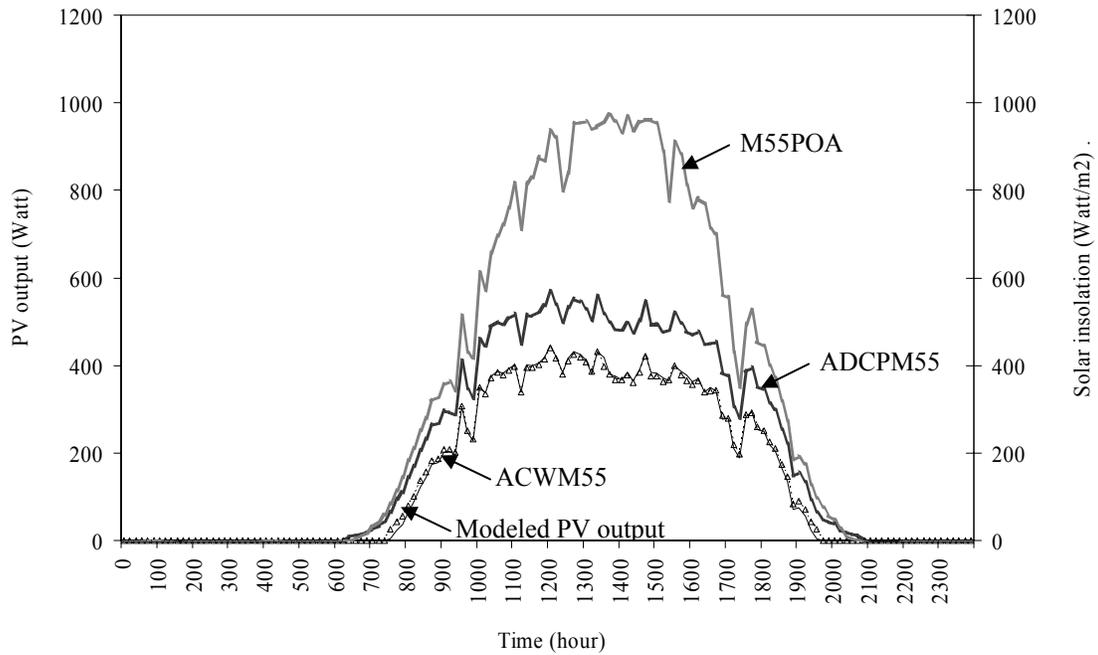


Fig. D-2. Solar insolation (M55POA), DC PV output (ADCPM55), AD PV output (ACWM55) from VTSTF and the modeled PV output calculated using inverter efficiency as shown in Fig. D-1

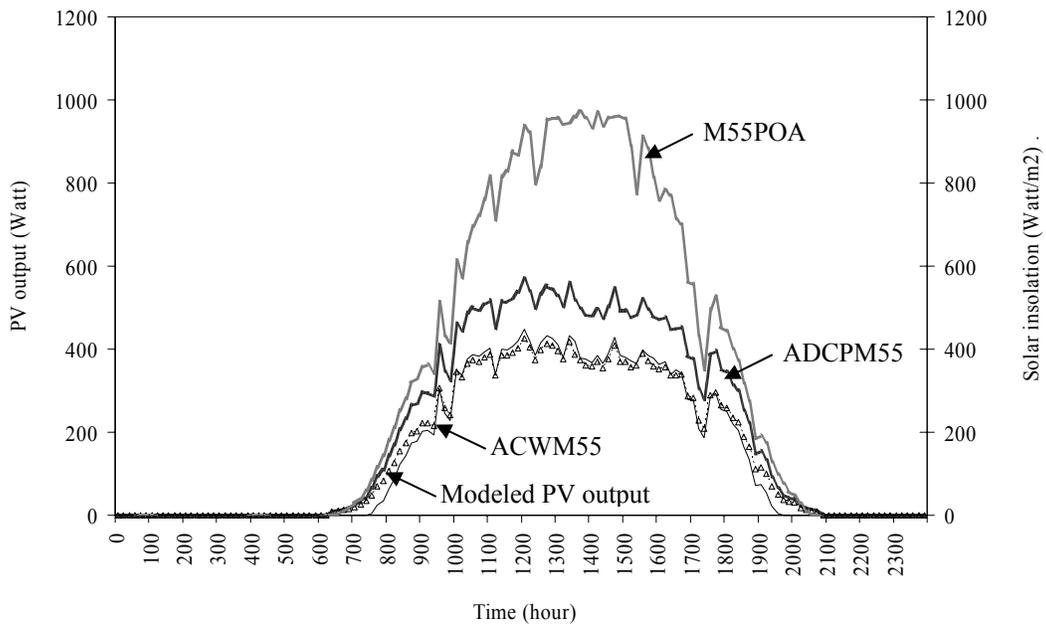


Fig. D-3. Solar insolation (M55POA), DC PV output (ADCPM55), AD PV output (ACWM55) from VTSTF and the modeled PV output calculated using inverter efficiency of 76%

The inverter efficiency value is determined based on one-year data of actual PV output. This can be done by comparing the annual summation of hourly actual PV output with the annual summation of hourly calculated PV output (based on eq. 4-17), and varying the inverter efficiency (η_{inv}) until the difference between the two factors is less than 0.1%. The inverter efficiency resulting from this methodology is 76%. Fig. D-3 indicates that the modeled PV output calculated using the constant inverter efficiency of 76% is within an acceptable level.

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