THE LOWEST COST ELECTRICITY FOR A POOR RURAL VILLAGE IN INDIA: RURAL GRID OR OFF-GRID SPV?

by

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ABSTRACT

Less than 50% of Indian villagers have access to grid electricity. Those who do have access find grid electricity unreliable. Hence, most Indian rural homes, electrified or not, continue to use primitive renewable energy from the sun, biomass, and cow dung for their day to day heating and cooking needs, while depending heavily on subsidized kerosene and diesel for lighting and irrigation pumping. A recent national government electrification plan for 80 million homes proposes $13 billion rural electricity grid investments out of which 90% will be capital cost subsidies. Access to 24 million poor homes will also be assured by 2012 with similar operating cost subsidies. However, my question is whether this grid electrification program is the cheapest way to provide electricity to India's rural poor.

The assumption behind the grid electrification of villages is that consumers prefer an unlimited and available “any time” power supply with no regard for the cost and the demand. With inadequate investigation of the customers’ ability and willingness to pay the true cost for good quality grid electricity, the current government's expensive subsidized plan will fail as have numerous past attempts with a continuation of poor quality of service and perpetual subsidies.

Very few studies have paid full attention to demand side factors to make clean energy sustainable and replicable in all villages without long-term subsidies in a competitive market environment. The literature lacks a theoretical framework to show that off-grid renewables like Solar Photovoltaics (SPVs) can be delivered at a lower cost than grid electricity under competitive market conditions now and in the future. Without this theoretical framework, the literature argues in favor of more subsidies to the rural poor for both the fossil-grid and renewables.

A body of literature exists from the 1990s about the role of emerging clean, competitive, culturally compatible, and climate friendly solar and biomass electricity as a rural energy solution. However, all academic literature, case studies, and government programs on renewables believe subsidies are inevitable (Taylor 2000; World Bank 2008). I disprove their belief. More particularly, the questions I will answer in this thesis are the followings. i) Is off-grid SPV electricity cheaper than grid electricity for the rural poor in India? ii) Can off-grid SPV electricity or grid electricity be subsidy free for the rural poor in India? iii) What are the break-even incomes for the grid to be cheaper than off-grid SPV? iv) Can this break-even income and consumption be reached for the electricity grid to be competitive or subsidy free by 2020?

A real life experiment lasting over 5 years in a poor electrified village in the Indian state of Orissa provides me the opportunity to model the demand for and supply of SPV and grid

electricity together. I show the potential for modern, off-grid SPVs to electrify the rural poor irrespective of their income level in this village, which has been electrified for more than 30 years but with a grid connection of less than 40% of households.

I use a "dominant firm" model to show the demand and supply interactions of both fossil-grid and off-grid renewables, contrasting their abilities to create and sustain a competitive market equilibrium. The model shows the theoretical possibility of a subsidy-free rural energy transition from an inefficient fossil-grid to more efficient renewable electricity. In particular, modern SPV electricity, though very expensive at present, is modeled as a decreasing cost, emerging technology with the added advantages of safety and portability. I find SPVs can displace the fossil-grid system at a lower one-time cost of $50-$350 per rural poor household, which is 10-70%% the cost of a grid connection. Operating costs for SPVs are lower as well.

The analysis suggests that with the current average rural income level of less than $100/month, the rural grid cannot be subsidy free. For household electricity consumption of less than 20 kWh/month, SPV electricity is clearly cheaper than the grid. The required threshold income to make grid electricity subsidy free is $196-$400/month. Even with the optimistic assumption of rural Indian income growth of 10% per year, these threshold incomes and a subsidy-free grid cannot be achieved in rural India by 2020 or beyond as the SPV prices are coming down but grid prices are not. The SPV supply, however, can be subsidy free at any level of income by designing small, modular, and very efficient end-use devices that are perfect for highly valuable portable rural applications that fit the conservation culture of the rural poor.

There are a number of implications of my study. Off-grid SPVs can not only challenge the dominant firm in the face of open access with no regulatory or market barrier subsidies to a particular technology, but they will eventually become dominant and competitive themselves. Not only should all subsidies for fossil fuels be removed, but appropriate taxes should be added so that consumers see the true costs of their consumption. The urban fossil-grid system should be separated from the rural off-grid renewables to improve the technical efficiency of end- use consumption, the commercial and market efficiency of the electricity supply chain, and economy-wide efficiency to make the off-grid renewables the lowest cost resources for sustainable development. Subsidizing the grid as well as off-grid technologies in rural India works at cross purposes, lacks focus on the most promising clean energy intervention, and destroys markets for both the electric grid and off-grid systems to achieve the critical scale of operation of both. Thus, I explore a long-term and least-cost solution to providing off-grid but modern renewable electricity from SPVs to over 80 million homes in Indian villages. These villages should be modernized and subsidies minimized with the overall economy set in a clean development path without the burden of rural energy subsidies and externality costs. Only recently, with the global climate debate, World Bank (2009) and IEA (2008) have picked up the fight against fossil-fuel subsidies. Thus, this study will be a timely addition to the literature of the technological possibility and economic success of off-grid renewables for providing subsidy-free modern rural energy for sustainable development without fossil fuel subsidies.

My experience working in the power sectors in both India and the USA along with my rural up bringing around the poverty stricken Orissa villages provide much of the first-hand information for this thesis. My interest in this topic was partly sparked by my 15 years of work in the Indian Ministries of Industries, Central Electricity Authority, and Central Electricity Regulatory Commissions. Over 5 years of recent experience working in a large investor owned diversified utility, Integrys Energy Group, dealing with both urban and rural Wisconsin and Michigan and competitive power markets across the USA, brought more insights to the potential for a competitive market for rural India. My graduate academic studies in electrical engineering, economics, and business finance, of course, provided the theoretical basis to effectively deal with the complicated interactions of electricity and economics in this thesis.

TABLE OF CONTENTS

ABSTRACT iii

LIST OF FIGURES x

LIST OF TABLES xiii

ACKNOWLEDGEMENTS xv

DEDICATION xvi

1 CHAPTER - 1 INTRODUCTION 1

1.1 Motivation 1

1.2 Contribution to Literature 2

1.3 Research Objectives 7

1.4 Outline of the Research 7

2 CHAPTER - 2 LITERATURE REVIEW 9

2.1 Fossil-grid Paradigm Works Well in Urban/High Income Markets 10

2.1.1 Wholesale market development and grid energy cost 11

2.1.2 Urban electricity market (Regulated Price Pu) 15

2.1.3 Rural electricity market (High cost LACr, Price Pr) 19

2.2 Fossil-Grid Paradigm has Problems for Rural India 20

2.2.1 Rurality: High cost of the rural grid unlikely to go away 22

2.2.2 Poverty: Low demand for electricity 30

2.2.3 Market inefficiency of monopoly fossil-grid perpetuate subsidized rural grid andnon-technical costs 35

2.3 Renewable-Grid Paradigm 49

2.3.1 Rurality: Renewable-grid will increase rural grid costs 49

2.3.2 Poverty: Requires small-scale affordable but reliable electricity systems 52

2.3.3 Inefficiency and monopoly: Renewable grid will need higher rural subsidies 53

2.3.4 Renewables in decentralized mini-grid systems not ripe yet for rural poor in developing countries 54

2.4 Off-grid Renewable Paradigm 56

2.4.1 Rurality ensures availability of low cost off-grid renewables 57

2.4.2 Rural Indian poverty and conservation culture lowers electricity demand,

but shows willingness and ability to pay for quality electricity. 66
2.4.3 Evidence of off-grid SPV's efficiency and competitiveness 69
2.4.4 Off-grid renewables promote market, competition, and efficiency now and in the future 71
2.5 Summary of Literature Review 74
3 CHAPTER – 3 THEORY AND METHODOLOGY 79
3.1 Theoretical Framework for the Research Questions 79
3.1.1 Demand and supply models for static equilibrium analysis (Q1-Q2-Q3) 80
3.1.2 Dynamic "dominant firm model" to estimate the future equilibrium outcomes 81
3.2 Market, Cost and Demand Curves for Rural Dominant Firm 85
3.2.1 Conventional fossil-grid costs 86
3.2.2 Fringe supply cost drivers 87
3.2.3 Modeling a log linear demand for the rural village households 88
3.3 Rural Dominant Firm Model with Off-Grid SPVs 89
3.3.1 SPV exogenous cost -reduction and increased income will drive a competitive market 91
3.3.2 The increasing grid cost cannot make the demand supply meet in the future 92
3.4 Varieties of Data Sources and Need for a Conservative Analysis 92
3.4.1 The fossil grid cost variability 92
3.4.2 The off- grid SPV cost variability 93
3.5 Selecting Dominant Firm to Answer Q4 if Grid can be Subsidy-free by 2020 94
4 CHAPTER – 4 VILLAGE CASE STUDY AND DATA 97
4.1 Outline of This Chapter 97
4.2 Village Selection 98
4.3 JABA Village Description 99
4.4 Data Gathering and Analysis 102
4.4.1 Preliminary data analysis 103
4.4.2 Income, expenditure budgets and spending profile 105
4.5 JABA Village Energy Data Analysis 108
4.6 JABA Village Renewable Energy Feasibility 113

4.6.1 Energy endowment and technology selection (Orissa state and JABA village)..... 113
4.6.2 Solar lanterns introduced at individual family level 117
4.6.3 Observation of a phased development plan 121
4.7 Summary of the Case Study 125

5 CHAPTER - 5 THE RESEARCH QUESTIONS 127
5.1 Q1- Is the Grid Cheaper Than Off-grid SPV Electricity? 130

5.1.1 Step 1: Determining components of LACr 134
5.1.2 Step 2: Average cost of SPV electricity (Ps) 146
5.1.3 Step 3: Cost comparison of SPVs with the Grid 149
5.2 Q2 - Can Fossil Grid or Off-grid SPV Provide Subsidy-free Electricity in Rural India? 160

5.2.1 Demand curve analysis 160
5.2.2 Step 1: Market definition and the Demand Model 162
5.2.3 Step 2: Demand modeling of poor homes 165
5.2.4 Step 3: Equilibrium consumption of the SPV supply and demand 169
5.2.5 Step 4: Equilibrium consumption of the grid supply and demand 170
5.3 Q3 - What are the Break-Even Incomes and the Break-Even Electricity Consumption for the Grid to be Cheaper Than Off-grid SPV? 172

5.4 Q4 - Can Threshold Income and Consumption be Reached to Make Grid Subsidy Free and Competitive with SPVs by 2020? 173

5.4.1 Step 1: Is the rural grid firm dominant today? 175
5.4.2 Step 2: Reducing SPV costs, increasing grid costs, and increasing demand 176
5.4.3 The unsustainable dominant grid firm when SPVs have lower price risk and non-cost advantages 180

5.5 Summary and Policy Recommendations Based on Cost and Demand Studies 182

6 CHAPTER – 6 LESSONS LEARNED AND IMPLICATION OF STUDY 185
6.1 Phase I: Energy-only Solution for Light, Lifestyle Comfort for Rural Poor 185

6.1.1 Opportunities to counter the energy divide and elite capture in JABA village 186
6.1.2 Short term barriers to entry of SPV showed up in Phase I implementation 187
6.1.3 Long-term structural challenges observed in Phase I energy-only initiative: 190
6.2 Phase II: Developing Sustainable Villages by Phasing in Off-grid SPVs for Meeting Modern Inputs and Outputs: 192

6.2.1 Observation of an integrated development 192

6.2.2 Phase II Principles: Energy for producing more balanced outputs 193
6.2.3 Barriers to high electricity demand in Phase II implementation: Skill and infrastructure shortages 194
6.3 Transition to Phase III in Search of Renewables Based SKILL 196
6.3.1 Technological opportunities of sustainable rural development 198
6.3.2 Small scale economic optimization in Phase III 201
6.3.3 Summary and potential funding: Emission /carbon offset trading 202
7 CHAPTER-7 CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK 205
REFERENCES CITED 215

LIST OF FIGURES

Figure 2-1 Market and technological representation of wholesale electricity market 13

Figure 2-2 Supply and demand curves in the rural grid contrasted with the urban grid at the top.. 16

Figure 2-3 Structure of the central grid network with short urban feeders serving many customers and longer rural feeders serving few customers 17

Figure 2-4 Transmission and distribution losses of Indian utilities increasing 27

Figure 2-5 Indian rural electricity market, HV and wholesale markets 28

Figure 2-6 Grid Electricity market does not exist in rural india 31

Figure 2-7 Two decades of poor financial health of Indian power sector (1990-2009)................ 37

Figure 2-8 Indian rural electrification priming up after lost years of 1991-2005.......................... 43

Figure 2-9 Average annual grid capacity additions in India with renewables 48

Figure 2-10 A simplified schematic diagram of the off-grid SPV system 57

Figure 2-11 Which is cheaper: rural grid or off-grid SPVs? 66

Figure 2-12 No need for off-grid SPV subsidies irrespective of income high or low, market clears all the time. 69

Figure 2-13 Grid parity of solar photovoltaic in lower latitude countries with the high solar radiation 73

Figure 3-1 Equilibrium of SPVs for poor income, where grid has none...................................... 81

Figure 3-2 Horizontal supply curves of off-grid renewable and solar PV as back stop................ 82

Figure 3-3 Rural dominant grid showing its decreasing viability of and increasing economic supply of SPV horizontal supply curves of off-grid SPVs as a back stop 84

Figure 3-4 Log-linear electricity demand model touching Q axis and outward shifting at higher incomes.. 89

Figure 3-5 Rural Dominant Firm Model showing decreasing viability of grid supply and increasing SPV supply 90

Figure 4-1 Location of the JABA village in eastern coastal state of Orissa in India 98

Figure 4-2 JABA village in the Mahanadi river delta of Orissa's Katak district.......................... 99

Figure 4-3 JABA operation villages are in the middle of plain land of Mahanadi delta............. 100

Figure 4-4 Closer view of the area surrounding JABA village 100

Figure 4-5 JABA village on one side of the small stream Kundi 101

Figure 4-6 The land and resources of the stratified village 104

Figure 4-7 Housing and electricity consumption of the stratified JABA village........................ 104
Figure 4-8 Electrification in JABA village by numbers in each caste group (2003) 110
Figure 4-9 Kerosene lanterns in a grid electrified home 111
Figure 4-10 Endowment of Solar energy in Orissa... 116
Figure 4-11 Demonstrating solar and LED lanterns 118
Figure 4-12 Contrasting multi-purpose SPV portable light with the rigidly fixed grid electricity light in rural application for poor 119
Figure 4-13 Roadwork at nights using solar lantern to avoid the scorching heat in summer 120
Figure 4-14 Solar power removes rural darkness and drudgery 122
Figure 4-15 Solar water pumping during building construction which require either manual or very low 40-100W efficient DC pump... 122
Figure 4-16 Solar lights installed by a local technician on village streets, solar street ligh near the BioCafe in a formerly pitch dark unsafe street corner 123
Figure 4-17 SPVs to power an energy efficient off-grid building with classrooms equipped with laptops, lights, fans, projectors, and LEDs for day and night activities, which also works as the health, adult learning and entertainment center 124
Figure 5-1 Equilibrium of SPV and grid for poor homes: Computational steps with targeted consumption Q_r*= 30 kWh/month/household... 133
Figure 5-2 The average fixed cost curves at various capacity levels and a composite average ADCr curve at increasing capacity levels... 142
Figure 5-3 Economies of scale in installed capacity cost of a LV distribution transformer........ 143
Figure 5-4 LACr based on the peak load capacity and monthly capacity charges 144
Figure 5-5 Cost curves grid vs. solar in a single Figure to show their competitive positions 150
Figure 5-6 The effective price with efficiency is much lower Pe = (Ps*Qs + Pef*Qef)/Qr........ 154
Figure 5-7 Total marginal costs of fossil-grid, renewable grid, and off grid SPVs 159
Figure 5-8 Equilibrium of SPVs and grid for poor homes 162
Figure 5-9 Data from the village case study to be used for regression study 166
Figure 5-10 Demand curves of JABA village at various income levels Y................................. 170
Figure 5-11 Poor and average income customers with no grid equilibrium will need subsidies at all level of consumption... 171
Figure 5-12 Income of $400/month is minimum required for 1 KW grid capacity. 172
Figure 5-13 Threshold income and consumption of rural grid to be subsidy free 173
Figure 5-14 Rural Dominant Firm Model 174
Figure 5-15 Demand increase simultaneously with the SPV cost reduction constraint grid dominance.. 176
Figure 5-16 Effect of household income growth on SPV consumption.................................... 179

Figure 5-17 Demand increase simultaneously with the SPV cost reduction 179
Figure 6-1 Social segregation and energy use: High grid and kerosene subsidies as barriers to entry for off-grid SPVs. 187
Figure 6-2 Phase II: ADI-RE-HELP expanded from the restricted Phase I using local clean and renewable energy for sustainable community development (most HELP services will use remote electronic services to reduce the transportation costs) 194
Figure 6-3Phase III: ADI-RE-SKILL-HELP phase optimized for clean, sustainable rural development (most external factor and output services will use distance based tele-services).. 200

LIST OF TABLES

Table 2-1 The calculation of cumulative loss % at each voltage level 29

Table 2-2 Indicative rural and urban incomes and consumptions in India and USA.................... 30

Table 2-3 Subsidies in rural grid electrification 33

Table 2-4 Retail electricity markets charge lower industrial tariff reflecting the lower costs in 2006. 33

Table 2-5 Social cost of the USA grid: Pollution, politics and friction 47

Table 2-6 Supply costs of grid vs. renewables: Current and expected trends, ... 51

Table 2-7 Comparison of commercially available battery technologies competing in the off-grid market 61

Table 2-8 Potential of off-grid SPVs where the grid has failed.. 68

Table 2-9 Off-grid subsidies for SPVs in some developing countries 69

Table 2-10 The advantages and disadvantages of the grid and SPVs 77

Table 3-1 Summary of the learning curve and price reduction of SPV modules in the past......... 91

Table 4-1 The state of JABA village: demography, income and some recent energy transition. 103

Table 4-2 Household data (monthly averages) 105

Table 4-3 Income sources and activities in JABA village in 2003 107

Table 4-4 Occupation in JABA village in 2003 107

Table 4-5 JABA village household electricity use and incomes 108

Table 4-6 Comparisons of JABA village energy consumption with that in India, Eastern India and Orissa.. 109

Table 4-7 Number and types of appliances in 2003 used by the electrified households............. 110

Table 4-8 What the villagers need the most-Not Energy 111

Table 4-9 What is subsidized the most? Grid electricity! 113

Table 4-10 Basic statistical summary of JABA village demography, energy and incomes 126

Table 5-1 The definitions of variables and functions used in computation of LACr.................. 134

Table 5-2 Summary of Indian electricity prices as traded in wholesale market Pw 136

Table 5-3 Estimate of the rural grid distribution fixed costs for a village................................. 139

Table 5-4 Cost of distribution capacity (Pc) at various levels of grid electricity usage.…….….141

Table 5-5 Average Cost of lighting energy for Rural Use for Qr = 30kWh/month 143

Table 5-6 Intermediate parameters and variables used in Q1... 145

Table 5-7 SPV average electricity costs TCs compared with the grid 148

Table 5-8 Average cost of inefficient electricity in rural lighting 151

Table 5-9 The efficient appliances are used in the off-grid SPV systems 152
Table 5-10 Average cost of lighting energy for rural use 153
Table 5-11 The self-financing nature of the cost of efficient appliances used in the SPV system. 153
Table 5-12 Cost of efficient lighting is about 1-4 c/kWh 155
Table 5-13 Over $18 million in off-grid SPV cost savings compared to SPV-grid in India 158
Table 5-14 Variables and demand equations to be estimated and determined 161
Table 5-15 The cost of kerosene light equivalent of Edison bulb in c/kWh 164
Table 5-16 JABA village average group wise data for household electricity demand modeling 165
Table 5-17 Descriptive statistics for the 98 households sampled in the village: energy consumption, prices, and incomes 167
Table 5-18 Regression demand results for JABA village 167
Table 5-19 Economic significance of parameters of the demand model 168
Table 5-20 Consumption, income, and price elasticities and the budget share for the very poor in rural India: 169
Table 5-21 The comparison of the restrictive assumptions in favor of grid verses actual observed values 184
Table 6-1 Renewable energy for lighting, information, cooking, weatherization, transportation to RE-HELP in a phased manner 198

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I must thank many friends in India and the USA, especially the trustees of ADIRE, IAFF, INDUS, and SHAMA, for the time and effort they have contributed to raise money for this project. I must thank both WPSC and Colorado School of Mines for the partial tuition support for my PhD study.

DEDICATION

To the small JABA village, where growing up within extreme poverty, I experienced the greenery of nature during the formative years of my life,

To my late father who inspired me to bring changes to the poor villages of the world through new technologies, new organizations, and new ideas.

CHAPTER -1

INTRODUCTION

Mumbai, India was one of the first cities to adopt the electricity grid and Edison's incandescent light bulb in the year 1882, along with New York and London. However, while the USA, UK, and even China electrified almost all of their households, India still remains the most electricity-deprived country in the world, where more than 400 million people in 78 million homes are without access to electricity with no signs of change (World Bank 2009;2004; UNEP 2008; Cust et al. 2007; MOP 2003; 2005). This is the state of darkness in a country more than 125 years after the first bulb was lit. The fact that more than 50% of rural, poor households in India are still un-electrified despite over a century of the electricity grid exposes deeper problems in grid technology for the rural poor.

1.1 Motivation

The motivation for this research started with my long experience with the repeated electricity market failures in India. The fossil grid problem is not limited to my village, but to all of the rural poor economies of the world. The International Energy Agency (IEA 2002) has reported year after year that 1.6 billion rural poor in the world are cut off from the grid, and the situation has not improved in the last decade. The population growth in rural areas easily offsets any possible growth in electricity connection in most of the un-electrified rural economies of the Indian subcontinent and sub-Saharan Africa. It is time to consider another approach. I will discuss two more motivations why we should explore a subsidy-free rural electrification plan that will remove darkness from rural areas.

Power interruptions in India are an everyday event not only in rural areas separated from the central grid by longer power lines but also in urban areas close to the grid. The reasons for the power interruptions can be attributed to the entire supply chain of the electricity industry: from the lack of the adequate power generation in base-load and peaking plants to the illegal connections and rampant power theft at the consumer end. Clearly, the quality of grid electricity in India is not suitable for modern living commensurate with the digital age that India cherishes. Thus, billions of dollars of investments in power quality improvements through backup generators, storage battery, and inverters are made even in urban India. The rural poor cannot afford that luxury. They have to reconcile with the age-old kerosene lantern. For the rich and educated, the lantern is a symbol of power failure, evening darkness, disease from indoor air, and deprivation of education and productive activities during evening times. Still, the lantern is so popular with rural India's 700 million people that a political party in India uses a hurricane kerosene lantern as an election symbol to entice votes from the illiterate poor. Rural India continues to depend on kerosene, causing economic loss through the negative externalities of local pollution as well as contributing to global climate change (UNEP 2008). However, I will show this lantern can now be powered by solar electricity at a lower cost than kerosene without the externality costs. Solar electricity can power cell phones, TVs, fans, and water pumps that can change rural darkness, disease, drudgery, and deprivation into a healthy, educated, modern, and productive rural lifestyle.

In rural areas, the cost of supplying grid electricity remains high due to the longer length of the distribution line, higher energy losses, poor load growth, and higher operating costs (NRECA 2006; IEA 2002; World Bank, IEG 1995; 2006). On the other hand, income-poor consumers cannot pay for the upfront and recurring costs of grid electricity (Modi 2005; World Bank 2002; Taylor 2000). The average Indian rural household income was about US$96 /month in 2008 (Shukla 2008) and will remain less than $300/month by 2020 even if an optimistic annual rural income growth of 10% is assumed. World Bank (2005) and NREL (1998) and Taylor (2000) assert that nowhere in the world can grid electricity be provided without subsidies to such low-income consumers. The provision of electricity in rural India is driven by government policy with a rural dominant grid monopoly that cannot charge even its short run variable cost (Dubash and Bradley 2005). Indian utilities lose 6-10 billion dollars annually, which is more than 20% of Indian industry revenue. These subsidies equal 1% of Indian GDP (GOI 2009).

Although the electric grid may have been a good solution for urban areas and rich economies, it has little to offer for the rural poor economies any time in the future. I therefore turn to the off-grid, small-scale, SPV-based development plans for electricity-scarce villages to see whether SPVs can address all these issues together. India alone has close to 600,000 villages in 140 million households in this category.

1.2 Contribution to Literature

The existing literature has largely ignored the true economic costs and overestimated the value of a small quantity of grid electricity of dubious quality to poor homes in rural India or any developing country. Rural grid electrification programs, from the New Deal of the 1930s in high-income USA to the most publicized, successful electrification programs in mid-income Chile, Peru, South Africa, Tunisia, China, and Thailand today, have all been subsidized. These subsidies are needed to compensate for higher upfront and operating costs in the face of lower revenue per mile in contrast to urban systems (Steven et al. 2009; World Bank 2000 - 2009). It is no wonder a high subsidy is part of the grid system everywhere in the low-income world. The grid expansion in India that started with a new Government scheme called Rajiv Gandhi Gram Vidyutikaran Yojana (RGGVY), a Village Electrification Plan to electrify all villages and 23.4 million poor homes, has been criticized by Bhattacharyya (2008; 2007; 2006), Singh (2007), Dubash and Bradley (2005), and Srivastava (2007) amongst others as likely to meet the target of rural wires but without electricity flowing through them. This plan is similar in objective to that of South Africa during the past decade that assumed that consumers prefer unlimited power 24/7 with no consideration towards their willingness and capacity to pay the cost of such high quality power. The high fixed costs of grid electricity in rural areas are known. Despite such high costs, the grid supply is not adequate, reliable, or safe in most developing countries (MAIT 2008; ISA-NMCC 2008; Wartsila 2009).[1] In India, the chronic shortages of peak capacity, 5-20%, and energy shortages up to 10%, have been reported by the CEA (2009) year after year for decades.

A few recent policy research paper including World Bank ((Khandker et al.2009) have argued that the benefits of rural electrification in Bangladesh and Vietnam surpass the marginal costs. However, my review of these study indicates that the grid electrification cover more affluent rural consumers only if the revenue per kilometer is more than $600 per month as in Bangladesh implying the cherry picking of already developed and rich customers for grid electrification. More than 70% of the rural households who are poor cannot pay the access and concurrent charges. All these projects are justified on socio-economic considerations with 100% capital subsidies and some operating cost subsidies still required even for the apparently richer customers. Such electricity projects could be argued to have positive spillover effects on the poor by way of more jobs in the rich households with electricity and ambient lights in the evening. But can these or even higher spillover benefits not be obtained from off-grid solar photovoltaic (SPV) and other modern renewable energy technologies while providing electricity to all without subsidies?

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[1] Often power failure is a common problem of all rural areas in the world though of differing severity. In the most modern grid of the world, I have heard of power failures in rural areas of upper Wisconsin and Michigan, USA lasting a few hours but they are almost unheard of in urban areas in normal situations. Our field experiences in the villages of Orissa, India show the down times due to thunderstorms, stolen conductors, and burnt transformers kept the electrified village in the dark for 10 days at a time in July 2009 (JABA Case study, 2009). World Bank (2001) reported the loss of load probability in the state of Bihar in 2000 on the order of 40%. In the context of India, recent reports by the NMCC (2006), MAIT (2008), and Wartsila (2009) bring out the costs of power failure in the range of between annual $10 billion for manufacturing down time alone to $60 billion for the entire country including the backup power supply costs. These power disruption costs range from 1% to 6 % of the GDP.

In the twenty-first century, modern technology has brought significant improvements in energy efficiencies, and renewable energy development has reached some technical maturity, especially the decentralized SPVS that I will show is the most appropriate for rural electrification of the rural poor. The cost reduction of SPVs over the last decade has been exceptional, with an average reduction in the price of 20% for each doubling of production (Prometheus 2009; IEA 2008; Schott Solar 2008; NREL 2002). The SPVs are now ready to compete with the grid in remote rural areas as indicated by much recent literature (Winrock 1998; Taylor 2000; IEA 2002; MOP 2005; Greenpeace 2008; Nouni 2008).

None of the past literature by the UN/World Bank, academics, or policy research and governmental organizations has clearly established or unambiguously accepted the possibility that currently available off-grid SPVs are sufficient to electrify and modernize villages. Bradley (1998), Taylor (2002), and Guru (2003) have outrightly rejected renewable subsidies while the World Bank and the Government of India (GOI) favor subsidizing both the grid and renewables as if they are complementary technologies in the rural areas of poor countries. All studies more or less accept the inevitability of the electric grid for development even though the grid monopoly is unfair and inefficient, with negative environmental externalities. Cato studies by Taylor (2002) and Bradley (1997) went a step further and even ridiculed renewable energy as neither clean nor green. One of their arguments that renewables are not cheap is valid in the context of the USA and developed countries that have enjoyed a reliable and safe electric grid for almost a century now and are still locked-in to a vast amount of fossil energy. However, a majority of Americans lived in urban areas and could provide subsidies for rural electrification during the U.S. take off stage in the 1930-1950s. Even the World Bank's economist (Saghir 2008) argued that the grid is so heavily subsidized in developing countries that the competitive off–grid suppliers do not have any chance of matching resources. A recent World Bank (2009) report, however, states that the subsidies made available to off-grid renewable projects are much less, 20-30% of the upfront costs, than for the grid. Even the Indian Ministry of New and Renewable Energy, which is supposed to promote clean and renewable energy has remained biased against the poor and rural areas (Miller 2009). Their top-down programs support large systems and big businesses to develop a market that is pro-rich and grid based and often anti-competitive (MNRE 2009; World Bank 2008; Redulovic 2006). The votary of competition and private capitalism, the Cato Institute (Taylor 2002; Bradley 1997) and the American Enterprise Institute (Joskow 2008; 2006; Green 2006; 2009) also support electric grid regulation and fossil fuel as inevitable.

None of these studies or any studies from MNRE and the UN system have analyzed the roles of off-grid SPVs for creating a low cost, competitive market in a conservation rural culture with a sunny climate where the necessities are mundane (food, drinking water, roads, and rain/storm proof shelter) that do not depend on huge amounts of grid electricity. Even where a huge amount of grid electricity has been supplied at subsidized rates, inefficiency and low productivity have plagued the grid and the end-use farm and household consumption. This opportunity of using SPVs was never available to developed nations during their rural electrification phase in alleviating the market failures of a monopoly fossil grid that, I will argue, have created some of the acute problems in the Indian electricity grid systems. These problems are high transmission and distribution losses up to 60%, high commercial losses of monopoly distribution utilities up to 30%, loss of national income up to 6% from inadequate and poor quality of power in urban areas (Wartsila 2009; MAIT 2009), and excessive ground water use (Dubash 2008), loss of soil fertility, and pollution (USAID 2009).

The same characteristics of rurality, poverty, and inefficient grid electricity supply that have moved rural India backwards can now be an ideal combination of opportunities for the application of modern renewable solar and biomass combined with the efficiencies of usage technologies to create a virtuous cycle for the transition to sustainable rural prosperity. Heavily populated Indian villages are the prime candidates for using modern technologies to leapfrog from extreme rural backwardness, because the expensive lock-in to inefficient fossil-grid technologies has not yet occurred. No country in the world has such a large un-electrified population in rural areas where the renewable energy resources of solar and bio energy are abundant.[2] Rural India might be saved from a futile and outdated development path because modern SPVs can achieve better lifestyle improvements at a lower cost now and at even lower costs in the future. However, not much research has taken place on SPVs potential. Whereas the renewable literature is saturated with cost benefit studies based on production costs none have looked at the demand side of the equation.

The World Bank rural electrification evaluation study (2009), based on historic data and willingness to pay, does not consider the true opportunity costs of energy and capacity of the rural distribution system. They also did not consider the future demand and supply curves of the grid verses SPVs, and if the same or better benefit cost ratio can be obtained from cleaner off-grid SPV energy systems.

I will show that modern SPV technology is cheaper than grid only electricity and requires no subsidies. Thus, it can be argued that if the grid subsidies cannot be removed, the SPVs deserve a fair regime where they get at least similar subsidies and market support as the rural grid in terms of per unit efficient energy use. SPV electricity can harness modern developments in energy generation and efficient use (examples: Compact Florescent Light (CFL)//Light Emitting Diodes (LED)//small Liquid Crystal Display (LCD) TV, irrigation and drinking water pumps at a household and farm level of consumption.

In a dynamic dominant firm model framework, I will consider the increasing demand of rural households possible through income effects and the decreasing costs of off-grid SPVs through learning curve effects using data from secondary sources. I will show that SPVs are not only competitive for the very poor now, they show increasing promise in the years to come. Thus, this thesis will be a valuable practical contribution to the theory of the dominant firm. It is the beginning of literature on the development of sustainable, subsidy-free competitive energy markets in rural areas that will promote similar studies and calm debates on global warming and the grid verses SPV costs in other developing countries. The study, by establishing the cost and demand superiority of the SPVS for rural modernization, will encourage international debate to focus on SPV based development to stop migration, dependence on fossil fuels, and decrease carbon and pollution emission.

The recent Indian government announcement of a solar mission for 20% of electricity to use massive untapped solar potential and skilled human resources by 2022 is also pointed in this direction. The stated objective of the solar mission is to drive down the SPV price to make it competitive with the retail price of electricity by 2020 and with coal plants by 2030 (MNRE 2010). Thus, this proposal is not only timely, but it will provide the theoretical and empirical support for the cost reduction of SPVs as well as to show the result of increasing subsidies for the grid if off-grid solar is not promoted to challenge the dysfunctional rural grid dominance. This will also bring about competition faster. By effectively separating rural areas from the urban electricity supply from two different sources, similar to what has been proposed by Reddy (1998), my research will show that the fossil-grid inefficiencies are not needed, but off-grid SPVs are necessary and sufficient for a clean, efficient and unsubsidized Indian village economy of the new century.

Much of the input data on energy consumption, income, and other human needs for a rural poor economy come from the development literature and my primary village development experiment. Similarly, the outputs of the study also inform the development literature about the costs, benefits, and potential role of competitive SPV markets. My research also has global implications for low cost clean development using renewable energy, energy efficiency, related skill and infrastructure in a competitive market environment.

1.3 Research Objectives

I have four research questions in this thesis. The first question of my research is to find out if the electric grid and solar PV can provide cheaper electricity to meet rural household and community demands with special emphasis on modern information, communication, energy, entertainment, educational, and electronic lighting (CFL/White LED) technologies, together designated as ICET. This question will be answered by comparing SPV average cost with the rural grid cost for the average monthly consumption of 30 kWh that the government has set up as the lifeline rate in rural India.

The second question of the research will be to determine whether fossil-grid and SPV electricity can be delivered in a competitive market without subsidies. I will evaluate the demand curves from the village in Orissa, and use the demand curves along with the long run cost curves developed in the first question to show that subsidies are essential for the grid but not for SPVs.

The third question is to determine how much income is required to provide subsidy free grid electricity to poor villages in India in a static framework. The rural electric grid has less opportunity to achieve the scale economies, considering the off-grid subsidies for kerosene and diesel and non-subsidized primitive biofuel the villagers use when their current average income is only $100/month.

The fourth and last question is the application of a dominant firm model. For this question, I take a dynamic look at the future when income, price, and technology will all have advanced. I ask whether subsidy-free electricity service can be achieved within the next 10 years when household income is still expected to be less than $300/month. A case study in the poor state of Orissa will provide model inputs and will illuminate the appropriateness and implementation issues of the cost effective and energy efficient SPV technologies.

The four questions are summed up below.

Q1. Is off-grid SPV electricity cheaper than grid electricity for the rural poor in India?

Q2. Can off-grid SPV electricity or grid electricity be subsidy free for the rural poor in India?

Q3. What are the break-even incomes for the grid to be cheaper than off-grid SPVS?

Q4. Can this break-even income and consumption be reached for the electricity grid to be competitive and subsidy free by 2020?

1.4 Outline of the Research

With this introduction to the grid verses off-grid debate, the detailed literature review for this proposal will be presented in Chapter 2. I will first describe how the fossil-grid paradigm, which has worked well in the developed world even in rural areas, has failed for rural India. I will show that rurality, which increases costs, coupled with widespread poverty, which reduces demand, makes the rural grid infeasible. Then I will show even if the technical grid supply and demand could be achieved with higher income or urban-rural joint management, the Indian fossil-grid system will continue the current high inefficiencies, poor quality and unreliable electricity. The many hidden externality costs will compound these problems. Then I will discuss the literature of emerging SPV energy technology and its potential for India in a grid and off-grid framework. The theory and research methodology of the off-grid SPVs will be described in Chapter 3.

A case study of a typical Indian poor village provides many of the experiment, inputs and insights for my study. I describe its energy endowments, the technological feasibility of off-grid SPVs for rural uses, and the methods of data collection from the village with a qualitative demand analysis for the households and community in Chapter 4. The modeling and analysis of demand and supply of grid and SPV electricity to answer questions 1-4 will be in Chapter 5. The results suggest that the removal of grid and kerosene subsidies can lead to a subsidy free unbundled electricity market in urban and rural India.

Chapter 6 will contain the practical observations of more recent case study research. They indicate the possibility of using SPVs, other local renewable energy, and energy efficiency to develop self-sufficient villages with the related skill, micro finance, and modern internet infrastructure for remote deliver of the necessary social and production services at lower costs than by conventional methods. In return the villages will provide to urban and developed countries emission offsets at lower costs than developing a renewable grid for urban areas. Chapter 7 will contain the conclusions of my research and suggestions for future work.

CHAPTER -2

LITERATURE REVIEW

My review of the literature initially focuses on both fossil energy and the electricity grid system (together defined here as the “fossil-grid”) for rural India. The review starts with the current state of the “fossil-grid” paradigm (section 2.1). As the focus of the thesis is to show the cost and pricing of fossil fuel verses off grid SPVS, a discussion of the theory and a literature review of the fossil-grid pricing in developed countries and in urban India are presented in section 2.2. However, rural India is a very different situation, and I will show the infeasibility of achieving a rural fossil-grid market and demand supply equilibrium in India.

I will then discuss recent attempts to supplement the fossil-grid with the “renewable-grid” in developed country markets in section 2.3. I note that currently the renewable grid is the only feasible solution for large rich urban areas to transition to renewable electricity. The rich economies can harness economies of scale and the monopoly grid can be successfully regulated, as is being done in developed countries. However, the literature includes two other kinds of renewable systems as competitors to the rural fossil-grid system: mini-grid and off-grid renewables. I will discuss the merits and demerits of these two competitors and argue that off-grid SPVs are most often the appropriate solution for the poor communities in rural India in section 2-4. Three sub-sections - fossil-grid, renewable-grid and off grid renewables - will deal with supply, demand, and the role of the market in competitive innovations and efficiencies for each of these technologies. Section 2-5 will summarize the lessons learned from the literature review and lead to the formulation of the four research questions. I will provide quantitative and qualitative evidence to support why SPVs have the best potential for electrifying the very poor, why I prefer using off-grid technology as the competitive fringe in a government subsidized “dominant firm” model, and how SPVs can be melded into the existing village culture and lifestyle while using modern efficient appliances and storage technologies. The summary in the last section will show that these off-grid SPV systems are clean, climate-friendly, competitive, and compatible with the village resources and conservation culture.

2.1 Fossil-grid Paradigm Works Well in Urban/High Income Markets

Modern central station generators in the large economies of the USA, European Union (EU), India, and China convert fossil, nuclear and hydro energy to electricity in many large plants (typical 500- 4000MW) close to the energy sources. The electricity voltage is first stepped up and then delivered through a high voltage (HV) transmission system of 100-735 kilovolts (KV) to load centers where they are stepped down to the medium voltage (MV). The electricity is then delivered through sub-transmission or distribution feeders to retail consumer premises. The generating plants, transformer substations, and networked HV lines constitute the core grid technology for an effective bulk power market for traders and also to minimize the generation costs.

By providing the benefits of load and resource diversity, the grid minimizes the need for generation capacity to meet the total peak load, optimizes the backup reserve requirement, and ensures reliability through redundancies of generation and transmission assets. For improved reliability during peak hours, smaller distributed generation systems with higher variable costs such as open cycle gas turbine, diesel, and old coal generators are retained at load centers as insurance against the possible outages of large generators, the transmission system, or excessive grid congestion (MISO 2009). These high cost standby resources also provide ancillary services like voltage support at load centers and start up services during system black outs (FERC 1996, Order 888). After a long spell of stagnation in grid technology, recent innovative smart grid ideas have come to the center stage to integrate modern SPVS and storage battery systems at key locations. In the future, it is expected that a smart grid will interconnect numerous plug-in vehicles to sell and buy energy (DOE 2009).

This technology, being large scale, capital intensive, and spanning a large geographical area, often needs to work under multiple state and federal jurisdictions, involving complex allocation of costs and benefits, investments, and entry and exit decisions, all of which are typically centrally coordinated. As the electricity grid is still expected to carry primarily fossil energy, about 60-70% in major economies like the USA, India, and China (along with some large hydro and nuclear power), to distant cities and village communities, the problems of fossil energy also become automatically integrated with the grid electricity.

We will see how developed nations have achieved success in the following three markets with special emphasis on the USA markets.

1. **Wholesale electricity markets** around the world are being made highly competitive through well designed market rules, vigorous market monitoring, and most of all by very high demand. Market innovations in the form of multilateral organized wholesale markets are

occurring in all large electricity markets of the world to bring price transparency, to reduce trade barriers, and to create an automatic market for energy imbalance that also simultaneously improves the grid's integrity and reliability.

2. **Urban electricity markets** in developed countries are not competitive but are based on the natural monopoly of the grid. Nonetheless, they have been made to work more or less efficiently through prudent cost-plus or price-cap regulations and high demand supported by the ability and willingness to pay.
3. **The rural electricity market** in the USA and developed countries also worked well with the initial support from the government coupled with a higher level and stronger growth in income to support the demand necessary for the grid to take advantage of scale economies.

We now look at each of these three markets in more detail to learn how efficiently they work, but why they cannot be ported to create competitive, clean and poor-friendly energy services to rural India.

2.1.1 Wholesale market development and grid energy cost

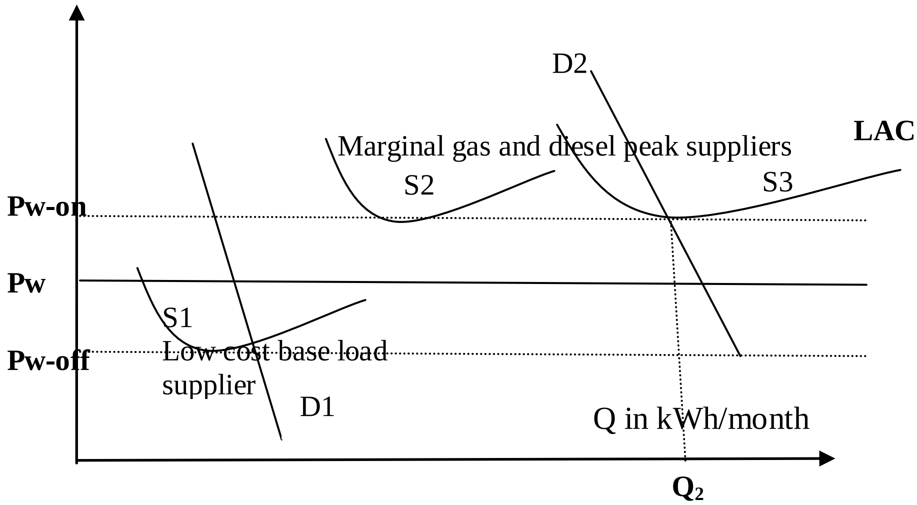
With natural monopoly, a single supplier can theoretically meet all of the market demand at the lowest cost. Multiple suppliers destroy the economies of scale of operation by splitting the low market demand as shown in the monopoly model of Figure 2-1a below demand D_1. Natural monopolies with lumpy investments show increasing returns to scale, and the average cost decreases for higher production (Dahl 2004). It is better for society to have just one supplier to meet the entire market demand at the lowest cost. The electricity market in the USA showed this trend for a long period. The demand was inadequate to support more than one energy supplier so monopoly was socially accepted for over a century with tight regulation over its pricing through regulatory commissions. Often, one large base load generator was being shared by two adjacent franchised utilities to reap scale economies of supply.

However, the electricity generator loses monopoly status with large demand as in D_2. Two or more generation suppliers as shown with the multiple U shaped Long-run Average Cost curves (LAC) in Figure 2-1 can meet the larger demand through a single, robust interconnected grid.

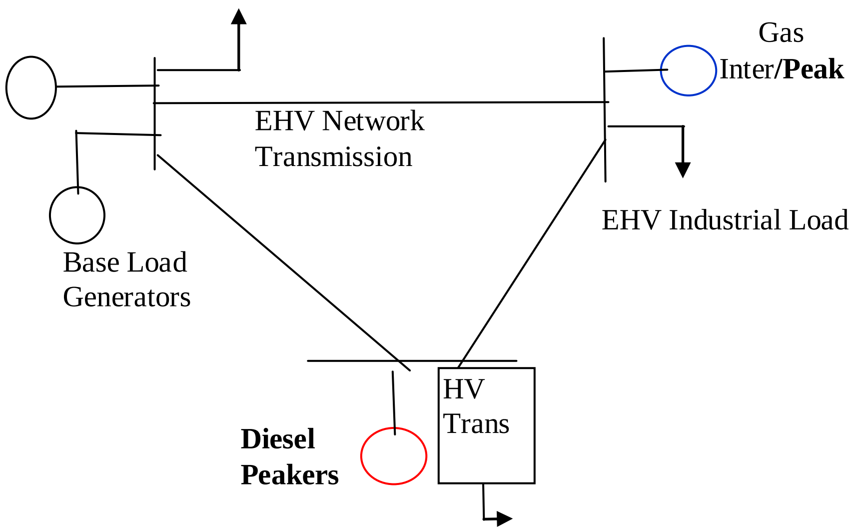
Under open access, with no barriers to entry and exit, no externalities, and no asymmetric information, this market is said to deliver competitive power at an average price of Pw for wholesale bulk buyers with high levels of demand. This price is time sensitive, often determined hourly, as demand shifts with weather, time of the day, week and year, and the hourly transmission and generation availability. Market based pricing with clear market price signals from the wholesale market encourages efficient power generation and end use of product and services. Vertically integrated utilities compete with independent power producers for wholesale market share. In Figure 2-1a, the vertically integrated monopoly also bids into the wholesale demand through various renewable and fossil-grid sources. The market operator selects the low cost bids in the increasing order of the marginal cost stacks, starting with the lowest variable cost resources. During on-peak periods, the market demand curve moves right and the high cost plants will set the marginal price that we denote as Pw-on. During the off-peak periods, demand will move left and set a low off-peak price such as Pw-off. Pw denotes the average price for the utility for all periods in a year. Such a competitive market works well in developed countries. For example, the wholesale price was 5 c/kWh in the market run by the Midwest Independent System Operator (MISO) on average in 2008, with a peak price average at 7 c/kWh and an off-peak average at 3 c/kWh. Internationally, the long run average wholesale price has been in a narrow brand in countries with high concentrations of coal-based power plants as markets of coal and capital intensive power generating equipment are internationally competitive (World Bank 2009; Dahl 2004).

The grid technology connects a large number of distance base load plants (coal, wind, and large hydro) though a complex network of transmission lines as has been simplified by a three node schematic system in Figure 2-1 b. The peaking plants, which operate only for few peak hours in a day, are powered by gas and diesel. They are often connected to the grid for local reliability and do not transmit power to distance places. Extra high voltage (EHV) customers can tap power from the wholesale grid directly at cheaper price Pw when they use power round the clock.

Such a wholesale market also works in a similar but not exactly the same manner for the newly emerging Indian national grid. About 15 wholesale licensed traders along with the state and private utilities buy and sell into the two centralized grid systems under a novel, frequency-linked, imbalanced pricing system reflecting the marginal cost of power every 15 minutes in real time. The Herfindahl-Herschman Index (HHI) has been about 0.18-0.33 suggesting a reasonable degree of competition. Prices have been increasing over the last two years of increasing demand signaling a need for investment. The market monitoring report of the Central Electricity Regulatory Commission (CERC 2009) shows the price in the Indian wholesale short-term power market to be over 10 c/kWh for most hours on average in 2008, increasing steadily until it touched almost 20 c/kWh in April 2009 during the peak hours.



a. Competitive Wholesale Market of Many Suppliers (Competitive Price Pw)
Source: Modified from Dahl (2004)



b. One line schematic of EHV/HV loop network transmission for operating a wholesale power market. Source: Author's simplification of the wholesale electric grid network with arrows showing the EHV/HV loads

Figure 2-1 Market and technological representation of wholesale electricity market

The above evidence suggests that the wholesale market works also in India when the transmission systems are robust, and demand (D2) is high enough to accommodate more players. In these markets, the marginal cost of generators, S3 sets the market price based on the system demand. Some infra-marginal plants like S1 get a market rent for their lower costs, which encourages cost reduction, a more efficient entry, and less market power. It is this wholesale market price that I will use for the peak and off-peak period as the respective variable grid energy cost (VC = Pw-on or Pw-off). The competitive Indian wholesale market will give me the economic cost of wholesale power (Pw) as the base energy price for my data collection and analysis subject to further adjustments for electrical transmission and distribution (T&D) losses.

The discussion above does not imply that the Indian wholesale power market is very efficient. It only shows that market-based prices are now transparently available as the opportunity costs of the grid electricity against the regulated prices that do not reflect true market demand. The one important inefficiency worth mentioning here is the poor capital investment that leads to the lack of network supply diversity and the high costs of on-peak and emergency power in the Indian wholesale markets.

Networked supply diversity: A well-managed system of flexible and complementary generation resources (base-load, peak-load, and fast acting) and a strong-networked transmission system with ample reserve capacity provide supply side diversity and reliable service in a wholesale market. Many large central station electric generators called base load stations convert primary fuel (such as coal, gas, nuclear, hydro and other renewable sources) to electricity with very high load factors of 70-90%. The extra high voltage (EHV) transmission network ensures the delivery of low cost power from a variety of geographically scattered, distant, diversified resources to a common wholesale market.

The load demand of numerous dispersed customers changes with very little notice, and when emergencies occur, the supply interruptions can be abrupt. Thus, the generation from the cheap base load plants often has to be supplemented with high cost peak load plants and other flexible resources that can act more quickly to meet any contingencies. The utility arranges for reserve generation and transmission capacity for possible planned and forced outages of the power grid or large generators. In order to ensure a cheap and reliable power supply, transmission and ancillary reliability services (such as voltage support, frequency stabilization, operating reserves, and black start facilities for emergency off-grid power supply to start a networked grid generator during grid-system black-out to name a few important ones from FERC Order 888) are also procured. A market for generation capacity and ancillary services is, therefore, enforced by the regulators to enhance the reliability of supply during all periods. Often these peak and flexible generation capacities are met by the low efficiency, high cost petroleum fuel engines or gas turbines placed near the load centers. If these high cost peaking power resources are operated only for short periods during the year, the grid electricity average cost is cheaper than installing new large central stations to meet the same peak loads with lower capacity utilization

The Indian wholesale market cannot attract sufficient investment funding for base load plants due to inadequate revenue flow from the distribution utilities. The overall cost of capital is very high in the electricity sector in India, often more than 15%. Thus, it uses mostly high cost diesel sets or inefficient coal plants operated for longer hours as the peak capacity as the larger, cheaper base load stations cannot meet the expanding demand with the investment shortfall, coal supply restrictions, and poor quality and availability of coal plants for the prime time. As a result the Indian total installed capacity of over 150 GW can typically meet less than 100 GW of nation-wide peak loads (CEA 2009). With similar market sizes, the Midwest ISO and PJM in the USA each meet over 100 GW peak load. Their reserve installed capacity requirement is only 14-18% over and above the peak loads. The plants are incentivized through pricing and monitoring to remain available during peak periods (DOE 2006; FERC 2009). In India the unattractive fossil fuel endowments, lack of adequate natural gas, and over-dependence on poor quality coal and expensive diesel as a peak and flexible resource reduces supply diversity and makes wholesale electricity more expensive. The average cost of wholesale electricity will remain high until the country has a more favorable investment climate and new technologies emerge to provide flexible resources.

Next we will move on to discuss how an efficient urban electricity market came into place in developed countries, how retail prices are determined and how the grid model was successfully ported to the rural areas. In the following section, we will show that this model has been attempted but has been far from successful in India.

2.1.2 Urban electricity market (Regulated Price Pu)

The medium and low voltage distribution feeders distribute power to load centers from the EHV networks of central generating stations through successive stages of step-down transformer substations located near load centers. In large urban areas, this distribution system is networked with enough redundancies, relays, and protection systems to ensure reliability by reconfiguring fallen lines or damaged equipment in any particular feeder. The urban electric grid network is a natural monopoly because it is considered inefficient to have two or more suppliers with multiple lines, maintenance crews, and corporate overhead costs to compete for customers on the same street. One supplier uses common assets and personnel to serve all types of customers inside a geographic franchise to harness the scale economies of distribution. Often, economies of scope are also harnessed by adding other similar network utility products, such as natural gas and water services to spread the overhead costs.

Even after a century, the prices in these markets are determined through regulatory compacts, unlike the competitive pressure of the wholesale market. A “just and reasonable” standard of price regulation has been adopted in the USA that ultimately ensures adequate returns to grid investors for them to invest enough resources to enable a reliable, high quality of supply. Such quality service in turn ensures that customers are willing to pay for the high value they get from the electricity services. Thus, the key point here is that well-informed regulators must keep constant watch on cost through utility cost audits, energy accounting, public participation, customer education, and service quality monitoring, and customers should find high value in electricity to make the circular cash flow for investment and service quality sustainable.

The retail market is not one uniform market of homogenous buyers but can be broadly defined into two groups with distinct pricing and competitive tendencies. Let us designate two markets, market u and market v to distinguish between the voltage levels of services by a grid supplier. Market u comprises the urban loads of a large number of small commercial and residential premises taking services at low voltages, using the entire chain of distribution assets - substation transformers, MV lines, line transformers, and low voltage (LV) lines. Market v is comprised of a small number of large commercial and industrial loads taking services only at high voltages without using any low voltage distribution systems. This is shown in Figure 2-2 as the horizontal price line Pu and Pv and in the circuit diagram in Figure 2-3.

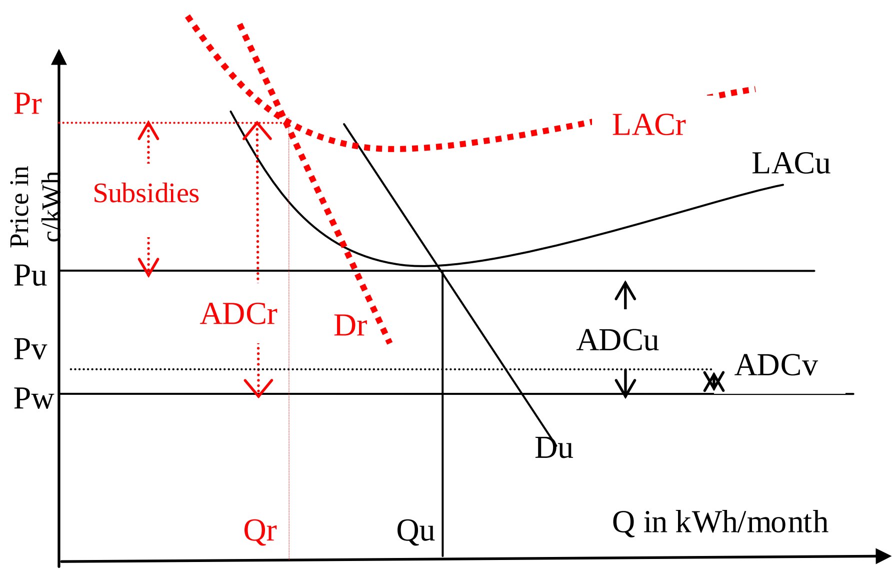


Figure 2-2 Supply and demand curves in the rural grid contrasted with the urban grid at the top

Figure 2-3 shows how the wholesale market serves the rural market through very long feeders and low customer density compared to the urban market which has longer feeders compared to EHV and HV markets. This schematic one line diagram gives an initial indication the high capital investments, operating, and high losses of the rural grid distribution systems that we will see in detail later in this section. Often to reduce the costs to rural customers the urban and rural facilities are clubbed together and no separate costs are recorded in the accounting systems in India or elsewhere. Further, due to poor power quality, all rich Indian rural and urban customers use a tailor-made battery-inverter system for their minimum power requirement during peak hours to run lights, fans, and TV. Businesses keep petroleum based small generators for keeping their activities going (Wartsila 2009).

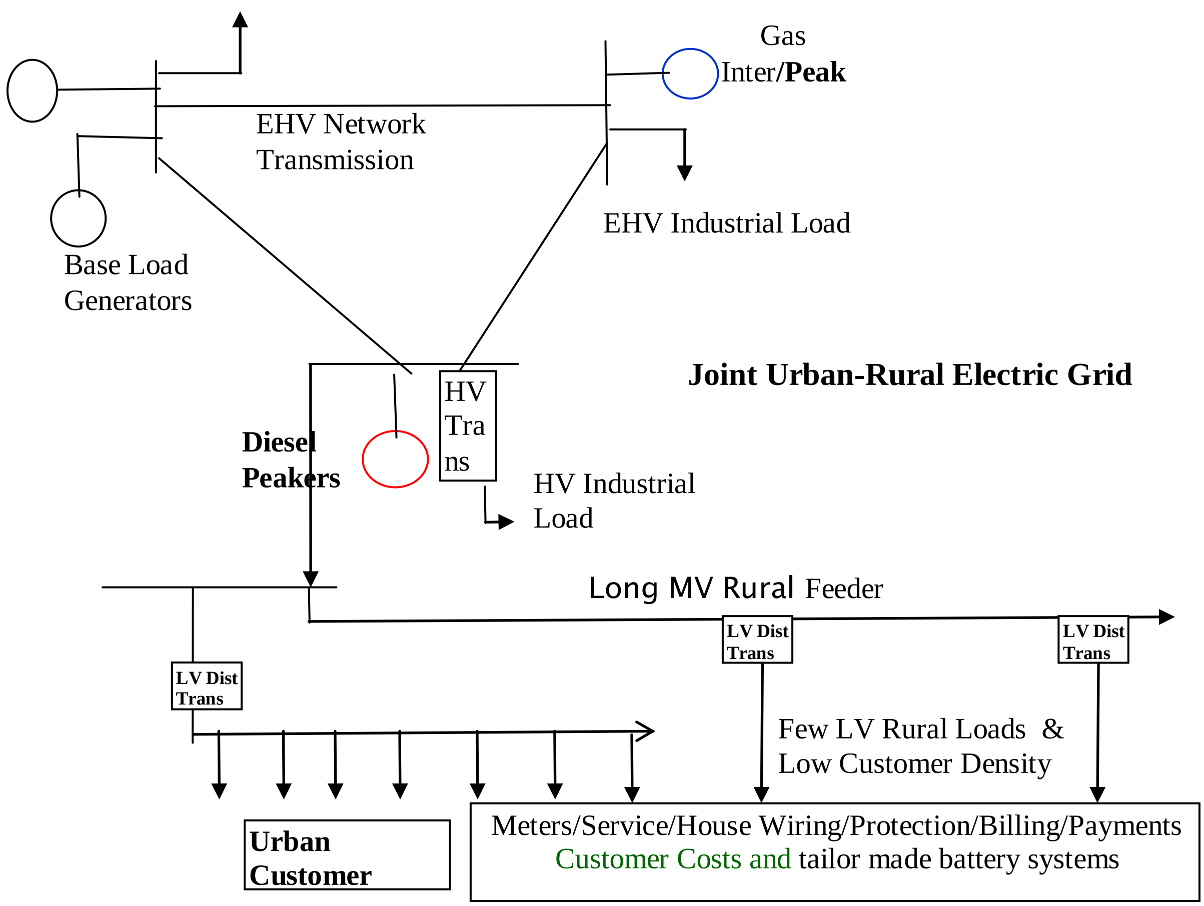


Figure 2-3 Structure of the central grid network with short urban feeders serving many customers and longer rural feeders serving few customers

Social and political bargaining involves a "cost of service" principle that fairly allocates costs at each voltage level in markets u and v. The long run average cost, LACu, shown in Figure 2-2 represents the average grid cost to deliver electricity to the low voltage urban residential market u. In addition to the power purchased from the wholesale market at price Pw, a margin ADCu reflecting the costs of all distribution facilities and operation and maintenance (O&M) is charged over and above the wholesale price, as shown in Figure 2-2. The total price to urban residential customers is now Pu = Pw + ADCu, where average distribution cost (ADCu) is the total distribution cost (TCu) spread over all energy sold, Qu. Mathematically, ADCu = TCu/Qu. The large industrial or commercial retail customers in market v, who use only the HV/MV facilities and no low voltage distribution lines and transformers, are priced at an appropriate average cost Pv, much lower than Pu and closer to Pw. Their average distribution cost, reflecting the HV systems, would be ADCv. The marginal cost to serve industrial and large business customers are much lower because they consume large quantities of energy at high load factors, often during off peak hours, yielding significant scale economies in distribution plant and O&M services. Off-peak hour consumption also helps lower the wholesale purchase costs.[3] I will show next that average cost pricing and any cross subsidies do not go well with open access competition, but marginal cost pricing does.

In a well-functioning electricity industry, it is important to charge customers a price that reflects the true marginal costs of services to ensure that their long-term consumption decisions follow the economic rationale where the marginal value of each dollar spent on the electricity for each consumer is equal. This marginal approach will also ensure fairness if customers pay the true costs they inflict upon the system. Urban residential consumers pay high prices as they use more distribution facilities during peak hours, and industries pay less as they use less distribution facilities and consume more during off peak hours. Thus, the transparent price signal minimizes cross subsidies and uneconomic consumption. This marginal pricing is also important for entry and exit decisions and the reduction of the overall cost of the electricity services to customers and the economy. If open competition is allowed and prices above true marginal cost are charged in market v, the large industrial customers closer to the wholesale market can easily switch to any lower priced competitor. New competitors can enter fairly easily and at a low cost with investment in some HV equipment required for delivering this new service. Even the industrial customer can tap the wholesale market themselves at lower prices by investing in these smaller distribution costs, when alternative suppliers do not exist. Thus, they can always bypass any high cross subsidy charged by the utility. In the long term, when and where there is open access to the wholesale market and HV transmission system, the dominant firm, including the urban natural

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[3]The fact is that ADCu and ADCv do not vary much with the energy consumption (except for electrical T&D losses) but mostly vary with the combined effects of number of customers, kW-load, and the nature of supply (HV/MV/LV/single phase /3 phase).This cost is often split into two components. The first one is a fixed monthly customer specific cost for meters, service drops, and customer services that do not vary with load and each customer in a group pays the same amount irrespective of energy and load. The second category is an average fixed demand cost (AFC) for transformer substations, poles, wires and O&M calculated in terms of $/kW/month. This cost varies with the load and is often based on the connected, contracted or actual peak loads.

monopoly, cannot charge more than the true marginal service cost of its competitors or the competitive technologies will eventually appear and threaten the market dominance of the incumbents.

Urban retail markets have not been made as competitive as the wholesale market, and the few states in the USA with open retail access have had mixed success in making them competitive (Joskow 2002; Joskow and Tirole 2006) But, one thing retail open access has done is to reduce the cross subsidy from the industrial to the residential sector. Thus, prices are more reflective of marginal costs driven by the threat of entry.

Overall, long years of cost-plus regulation and consumers' participation through citizen forums have made pricing and investment work fairly smoothly. Besides occasional short-term bankruptcies, as in California, no utility is allowed to go permanently bankrupt; governments intervene to absorb these risks.

The urban fossil-grid systems in India are also commercially viable and are successfully managed by private power companies in Mumbai, Surat, Ahmedabad, and Calcutta.[4] Most other smaller urban areas have to serve huge, low-income, rural irrigation and residential customers. In effect, such markets have characteristics that are more rural, and they face the unique market failures in typical low-income rural markets that we will review in the next section. A review of the rural grid in the USA and other mid-income countries will determine whether their models are relevant and adequate for rural India.

2.1.3 Rural electricity market (High cost LACr, Price Pr)

Rural electrification worldwide has always involved the political and social burden of providing rural people with an opportunity to use modern appliances, prime movers, and gadgets at lesser costs, replacing previously existing inefficient energy sources (World Bank 2002; NRECA 2008). The low revenue per mile of rural distribution in the face of higher costs creates a paradigm requiring a subsidized rural grid. In the case of the USA, as private investors were unwilling to serve the rural market, rural electrification started with subsidized power, technical assistance, long-term, and low-interest finance from federal agencies after the late 1930s under the "New Deal". The rapid rural grid electrification under this "New Deal" replaced traditional

[4] The only recent urban market failure in India is Delhi power distribution with relatively high income and very few rural customers. Its failure cannot be explained without factoring in the role of government ownership, bureaucracy, corruption, and moral hazard that are well documented by World Bank (2009) and will not be discussed here.

rural biomass heating, distributed mechanical power such as water wheels and wind mills from the USA by 1960 (USDA 2008). With high pre-existing annual household incomes at about $2000 based on 2008 real price, early USA grid managers had no problem with access but only had to increase demand and encourage load growth to harness economies of scale and reduce the average energy cost. The reduction in average costs could help provide low cost electricity service to the very poor. Electric heaters, cookers, irons, power tools, and incandescent bulbs could quickly add to rural loads. A high enough income growth in the 1950s and 1960s combined with rural electrification subsidies and low-income assistance supported such demand growth.

This high cost rural electricity market for a rural cooperative in the USA can be represented by the dashed higher long run average cost curve (LACr) in Figure 2-2. The demand curve Dr is expected to be lower than the high-income urban demand Du. The average rural distribution cost ADCr can then be determined as the meeting point of the Dr and LACr. Clearly, the ADCr is much higher than that of the urban ADCu. However, available rural subsidies, highly depreciated capital assets, low cost financing, no tax burdens, and growing income, not shown in the figure, might have brought the actual average rural electricity rate in par with the urban rates over time. Again, many investor-owned utilities (IOUs) who usually serve urban customers, still cross subsidize the peripheral rural customers through socialized rate making. The true LACr and LACu depicted in the figure are not visible to individual customers in most countries of the world due to direct subsidies, cross subsidies, average cost pricing, and lack of transparent data and separate accounting information for rural assets. In the next section, I will show why the above model will not work in rural India.

2.2 Fossil-Grid Paradigm has Problems for Rural India

The conventional electric grid system will continue to face the challenges of "rurality" "poverty" and "electricity market inefficiency" that overflow to the entire Indian electricity as well as economic systems. Rurality with low population density and away from the existing urban areas implies high grid expansion and operating costs. I will show in subsection 2.3.1 that such a high cost of rural supply requires a perpetual subsidy. Low usage resulting from extreme poverty contributes to added costs as well.

Past literature has only considered high grid costs as a result of distance and technology, while exploring grid solutions and comparing the costs of alternative off-grid renewables. (Nouni et al. 2005; 2006; 2008). When comparing the alternative energy technologies (heat and electricity) to the electric grid, Nouni et al. have not considered a second poverty-related feature, low demand that increases the grid average cost. The income poverty literature of rural areas is abundant in the World Bank and UN systems and has been intensively discussed by Bhanumurty (2000), Dutt and Ravallion (2002), Shiv Kumar (2002), Sachs (2005), Easterly(2006), and Sen (2008). Poverty and rurality are intrinsically linked worldwide. Although top-down development, based on the fossil-grid fuel, can help create high urban-income, the grid is hard to port to poor and rural societies (Lewis 1955; Lucas 2004). In such rural places, low income does not create a high enough electricity demand to make the grid economically viable. However, low demand does not increase the average cost of low scale SPV energy because of its modularity. The fixed costs can be reduced by designing off grid portable devices to be small enough to be affordable to even the poorest inhabitants. Cleaner SPV-LED lighting and biomass cooking systems can be designed to be small enough to be suitable for poor domestic needs at a cost of $5-$20, the cost of a flashlight just a few years ago.

The third issue is the time and market inefficiencies (monopoly, power quality, and scarcity) dimension shown in subsection 2.3.3. They increase the customers own costs due to disruption and safety risks arising out of lost peak loads, poor reliability, scarcity, terrorism, and war. The studies above by Nouni et al., which found the grid competitive to SPVs in rural areas within 5-25 kilometers of the existing grid, did not consider the poor reliability and peak time dimensions that increase grid costs. All these additional economic factors, low demand, poor quality, and higher risks of grid power are not well researched but are helpful to explain why most of the homes in electrified villages in India are not connected to the grid even if the electric grid is available right in front of their homes. Furthermore, in the absence of reliable and adequate electricity, most of India uses polluting “off-grid fossil fuel”, such as kerosene, diesel, and candles, in addition to primitive renewables - biomass and cow dung (Ravindranath et al. 2005; Seetha 2009; UNEP 2008). This arguably creates one of the most inefficient energy systems in the world.

The literature review in this section will shed some light on three complex grid issues: rurality that drives up the direct grid industry costs, poverty that reduces the customer’s affordability, and negative externalities and electricity market inefficiencies that increase the indirect customer costs (battery/kerosene back up costs hidden from the electricity market price). The only way the grid can be both clean and competitive is if cost decreases, demand increases, and negative externalities and inefficiencies are reflected in the market prices.

I will show in section 2-3 that none of these issues are solved in the SPV based renewable-grid paradigm, which is often promoted with more emphasis in urban areas to correct fossil energy scarcity and pollution impacts with much less importance in rural areas. Rather, I will show in section 2-4 that these three dimensions (rurality, poverty, electricity market competition/efficiency) are not only solved but will also be the actual drivers to introduce off-grid SPVs and to disentangle the rural energy market from the grid failures in India. Thus, both the urban and the rural markets can follow their independent and sustainable growth paths.

I will now deal with rurality to show how grid costs are high and cannot be reduced easily to compete against off-grid SPV alternatives in rural India.

2.2.1 Rurality: High cost of the rural grid unlikely to go away

Rural utilities in developed electricity markets normally procure capacity, energy, transmission, and ancillary services from the wholesale market to meet their customers' peak load for a firm, non-interruptible provision of electricity. The average cost (Pw) of these services from the wholesale market can be determined by the hourly costs of energy, capacities, and ancillary services. These hourly numbers can be grouped separately for the on-peak and off-peak hours. Utilities also incentivize retail, commercial, and residential consumers to reduce their peak hourly consumption by pricing high during peak hours and low during off-peak hours. Most industrial users try to use more electricity during night hours to take advantage of the cheaper off-peak power to reduce their costs. None of these peak pricing services are available in India, although new solid state meters make it possible to measure and bill hourly prices. With the negative generation reserve of 10-20% and inadequate transmission capacity, even the off-peak wholesale prices are not very cheap. An urban distribution grid can be designed with backup supply feeders to ensure reliability and sufficient reserve capacities. All these reserves, flexibilities, and redundancies in the electricity supply chain require large capital investment. These types of investment capital certainly do not exist in rural India. When grid power cannot even be delivered to load centers in urban India in a reliable and optimal manner, the skeletal power distribution system that exists now in rural India cannot deliver reliable electricity for modern ICET applications. Such a bare bone electricity distribution system will continue to exist in the future according to the present RGGVY plan in spite of its tall claim that rural areas will not be discriminated against compared to urban customers. Rural grid lines, which are farther from the urban areas, require higher investment and costly vegetation management, are subject to the vagaries of nature, and entail a longer travel distance for operation and maintenance crew. Thus, an affordable, safe, and reliable firm power supply is not expected in rural India any time soon. The cost optimality of the power supply system also breaks down due to demand side features such as lack of demand diversification during off peak hours, lack of industries, and inadequate growth of rural loads. Customers that value and can pay the true costs of reliable firm power do not exist in rural India. Thus, the supposedly subsidized rural grid electricity will continue to require back up energy for lighting, fans, and ICET devices as a separate out-market costs of the grid electricity.

High Technical Costs (A natural outcome of rurality and unavoidable)

The rural grid's true economic costs are higher than the urban grid costs for technical and non-technical reasons as listed below. The summary of technical costs will serve as a basis for further exploration of whether any of these costs can be easily reduced in the future. The non-technical costs will be dealt with in section 2-2-3. They include:

- Long lines and low voltage supply to serve scattered rural customers require expensive and massive capital investment per customer and kW load served
- High operation and maintenance costs to deal with many small customers
- High percentage of "transformer" and "line" losses (15-35% of the power input)
- Exposure to storms, warm climate, vegetation, stolen conductors along with animal and other human abuses in remote and unsecured grid assets
- Coincidental peak load of rural customers require expensive generation to supply peak energy and capacity

Capital and Maintenance Intensive: The rural feeders are always built with long overhead lines to reach the geographically dispersed communities. It is prohibitive to have networked distribution systems and ensure long, redundant feeders to maintain and operate these long lines in geographically dispersed communities. Millar (2000) indicates that the rural grid average costs could be 3-9 times the retail urban cost.

One positive attribute worth noting here is that the average construction cost of the Indian distribution system is at the lower end compared to the international costs as shown by NRCEA (2007). The lower cost could be due to lower quality and lower safety standards though a lower labor costs might also have been reflected in historically lower costs of Indian grid power. However, this cost advantage is easily offset by the poor capacity utilization and higher losses discussed below. Some of these low labor costs will benefit off-grid renewable power as well. Skill and safety levels can be enhanced in off-grid SPVS more easily as shown by the Barefoot College in India, which has trained thousands of women from poor countries to manufacture and disseminate SPV systems (Roy 2008).

Low Capacity Utilization: The load density is low on most of the rural grid; growth of load is also very slow as argued by NREL (Taylor 1998; Allderdice and Rogers 2000) and World Bank (1995). The lumpy nature of grid investments will not allow a small phased development of facilities to match the slowly increasing loads in poor villages. This increases the average costs of the grid supply for smaller loads and yields poor returns on investment. No literature discusses this slow customer addition in the rural grid and the problems with the recovery of the fixed costs. Thus, government taxes, donations, and international aid are the only funds that have been invested in the rural grid.[5] Rural loads are mostly related to light bulbs, TV and a few fans strongly coincident with peak load. The absence of refrigeration, freezers, heating, or 7x24 commercial and industrial loads, and streetlights during the night reduces the load factor and the economies of scale in rural consumption.

The cost optimality of the power supply system also breaks down due to demand side features such as lack of diversification and inadequate growth of rural loads as explained below. Customers that value and share the costs of reliable power do not exist in rural India.

Networked demand diversity/load growth: Normally demand side load diversity results in a lower combined total peak load for the system than the sum total of all customers' individual peaks, because some customers have peaks at different times than the system peak. (These peaks are called non-coincidental peaks.) Because of non-coincidental peaks, typically the system peak is 40-50% of the summed individual peaks in urban areas. Further, high revenue generating customers reduce the costs of reserves and redundancies per unit load and drive the economies of scale of the electricity business. The commercial loads of industries and streetlights in urban areas that provide load diversity by operating during off-peak hours are non-existent in Indian rural areas. Lights and TVs are used during the evening peak hours in rural India from 5 PM to 11 PM, when the system demand is high and peaking plants are run by expensive diesel sets. The rural load therefore is coincident with the power system peak leading to high costs for rural power.

The Indian government's recent rural electrification plan in 2005, called Rajiv Gandhi Grameen Vidyutikarana Yojana (RGGVY), has the goal of electrifying all households by 2012. RGGVY promises a supply of power for 6 hours per day and expects the state governments not to discriminate against rural areas. But this is complex to administer with little hope of enforcement. Even if enforcement can be assured, the costs of such on-peak electricity, purchased to serve the rural poor, have not yet been properly accounted for. It is now time to assess the real cost of this electricity by including the cost of on-peak electricity and the related distribution losses. To assess this cost, I will compare SPV electricity (which is intermittent, subject to the availability of sun light) with the rural grid, which is also intermittent, assuming the same level of battery backups for both technologies. Numerous studies by the government (CERC 2009) and

[5] Asian Development Bank (ADB) and World Bank financing, often driven by financial return, target urban and suburban areas with some consideration of the urban poor. The high transaction cost of working in rural areas stands as a barrier to these banks' role in rural areas. Miller (2009) shows some learning by the World Bank in the last few years while working for off-grid solar dissemination in rural areas.

international agencies (UNEP 2008; World Bank 2009) have already proved that SPV technologies are cheaper than the small diesel powered systems for electricity consumptions in off-grid rural areas. I will not repeat those cost comparisons but will ignore higher cost diesel based solutions for rural India.

High electrical losses: The rural average technical loss is high and depends on all possible unfavorable conditions: longer lines, lower voltage, higher current for a few hours in the evening, and a low load factor (average hourly load over the maximum load) most other hours. Engineers know that a higher peak load fraction at the same overall load factor increases the line losses more than a constant load fraction at the same load factor due to quadratic loss and power relationships (Pabla 2005). The losses from the electrical line in longer low voltage systems can be high for a few primary reasons: the leakages from corona and poor vegetation management and high marginal line loss from the few hours of evening peak use for lighting with almost no load off-peak.[6] Energy losses from poorly utilized transformers during off-peak hours are called magnetizing iron loss. With no off-peak load, the inputs to the transformers are 100% lost since the transformers serve no actual customer loads. Further, the marginal cost of line loss is more than the average loss due to the quadratic relationship between consumption and loss. More rural peak loads coinciding with the peak of the entire system will have higher marginal costs due to the copper loss impact. With low loads at off-peak hours and overloading during the peak hours of the rural distribution system, the marginal energy loss costs are much higher than the average losses.

In India, the nation-wide average T&D loss is 35% but in individual states, the losses are much higher. The state of Orissa has T&D losses of 40%-45% in various privatized utilities. These average losses again are the combined averages of both the urban and rural grid, where the urban grid has less losses and the rural grid has more. The rural loss can climb to as high as 68%

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[6] During no load or light load conditions most of the loss is related to the core loss for charging the transformers, leakage in insulators, line contacts with trees while serving no real load of the customers. The core loss is proportional to the voltage and depends on the nature of the core iron material. A cheaper transformer will have lower upfront costs but a high core loss wasting energy 7X24. Loss percentage is close to 100% during the off peak hours T_{off}; when the core losses and electrical leakages are the only load with no useful customer load on transformers and rural lines (e.g. midnight with no heaters, lights, fans, and refrigerators). During the high load periods in the day and evening hours T_{on}, the total loss $Tl = I_{on}^2 * R * T_{on} = (Q_d/V*pf)^2 * R * T_{on}$, called copper or line loss. It is proportional to the resistance R, determined by the length of the line, and the current I_{on}^2, where I_{on} is determined by the peak load demand $Q_{d,}$ over the voltage level V multiplied by a power factor pf representing the relative amount of energy transfer per unit current (real power/reactive power). The average line loss for a given peak load (or power Q_d in Watts) = $La= Tl/(Q_d\ T_{on}) = (Q_d/(V^2 pf^2))*R$ and the marginal loss is twice as high at $Lm= 2*(Q_d/(V^2 pf^2))*R = 2*La$. (Adopted from Pabla, 2005; Liu and Zobian, 2002). Low voltage distribution line, leaking insulators, and poor vegetation management that are responsible for higher loss can be reduced with high capital and O&M investments. However, this requires a costly trade off when the rural load and revenue collection is poor.

at low voltage levels, and power theft adds to these high losses (Kanungo 2001).

India attempted privatization, USA style regulation, and then went a full circle back to government owned power systems in the last two decades. However, it achieved very little efficiency from grid technology, which might be inappropriate for income poor rural areas. Even after restructuring, the averaging of electrical losses at various voltage levels can hide the true cost of rural distribution. For example, the loss in utility books will normally show up as a weighted average loss across all voltage levels and consumer groups. When a utility has more wholesale and HV customers, most of the power flows through shorter HV lines and the average loss will be lower than for the low voltage urban retail supply. In rural areas, the MV lines to feed power to distribution transformers (DT) are not only longer, but the LV lines that service houses away from the grid are also longer. These longer lines can double the cost from energy losses. The DTs, which are oversized for future load, are also not optimally used. They consume standby energy while waiting for the future consumers to connect at a slow pace of 5-10% of potential customers each year. The meter in the consumer premises does not read the losses that are wasted on these lines and transformers. Someone has to pay for the costs of the additional energy to compensate for the losses. Customers that are more rural, smaller, and farther from the grid will have higher energy losses. For all these reasons, the losses of the Indian grid are very high, as can be seen in Figure 2-4 and have increased over the decade. The original Orissa State Electricity Board (OSEB) in the state of Orissa had losses of about 20% during early 1993. The three red bars representing the three unbundled private utilities reported their losses at more than 40% in 2003 after restructuring. More transparent accounting and incentive of the independent distribution companies to show more losses, to be able cover these costs, led to such high losses for all unbundled utilities. Though these loss percentages are still estimates and debated due to the lack of metered data and robust accounting practices, high losses should not be very surprising for a utility with predominantly rural customers.

Although no Indian utility has estimated the increase in the real rural grid losses, recently a southern Orissa utility has claimed that RGGVY has increased their losses. OERC (2009b) has also alerted utilities in Orissa that they should be prepared for the higher O&M expenses that the rural grid will entail. If such assets are not well maintained (and most likely they will not be maintained for want of adequate revenue sources), the poor maintenance of transformers, insulator leakages, line joints, and growing vegetation is likely to increase the present average rural distribution loss of over 51% to a much higher percentage. The utilities with very low losses in the left part of the figure have the luxury of allocating many of the actual electrical losses in the free or highly subsidized power they sell to farmers. There is hardly any difference between free power, power theft, or electrical losses as far as utility revenue is concerned. This and the lack of adequate metering create many energy accounting issues in the Indian electricity sector that regulators are still trying to grapple with (Tamil Nadu Electricity Regulatory Commission 2010).

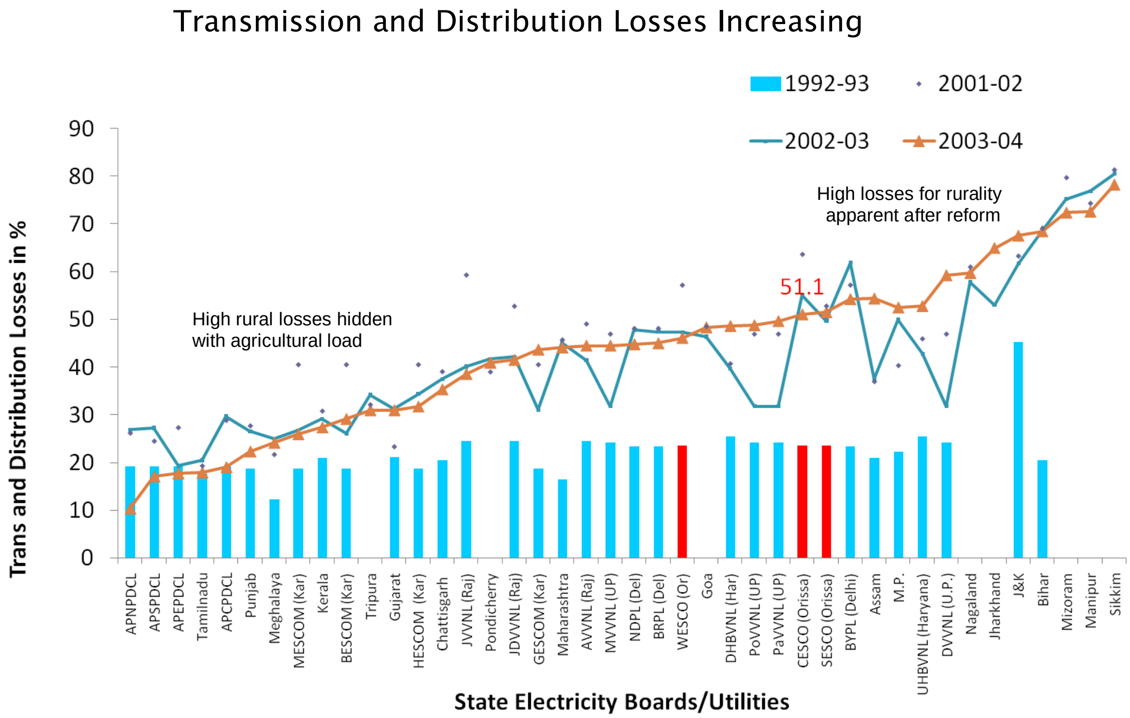

Figure 2-4 Transmission and distribution losses of Indian utilities increasing
Source: Compiled by author with data from Ministry of Power, GOI 2008

The estimated average 35% loss for the rural system is computed from information shown in Figure 2.5, which will be used in my cost analysis of the rural grid. In the figure, power flows through the extra high voltage (EHV) transmission system, HV sub-transmission system, distribution feeders, distribution transformers, and low voltage secondary system until it is measured at the rural customer's meter. In each stage of the grid, electrical energy is lost. The percentage loss is shown in parenthesis for each stage of the grid. Thus 4% is lost in the wholesale market and also about the same 4% is lost in the state owned EHV system for state generation plants and so on. The wholesale and EHV markets being electrically closer to the source of generation have lower losses and I will assume that the cost of such minor losses are already included in their market prices.

Although the urban distribution system uses most of the same stages as the rural grid, it will have lower losses than the rural system because it has shorter lines and a more optimally used distribution system. To compute total losses for the rural market from the wholesale power market to customer meter, I will accumulate the losses over all sections of the grid. Let I_i be the power input into section i of the grid (where starting from the wholesale power market i =1 is the HV substation transformers and feeders, i = 2 for DTs and i = 3 for LV lines and service drops). O_i is the power output from section i of the grid, and L_i% be the percentage loss in section i of the grid. Starting at the wholesale power market, if input from the market of EHV networks to the high voltage grid is I_1, then output from the HV system is $O_1 = (1-L_1\%)*I_1$. O_1 then become an input into the next section of the grid I_2. Output from section 2 is then $O_2 = (1-L_2\%)\ I_2 = (1-L_2\%)(1-L_1\%)I_1$. Output from the jth section of the grid is $O_j = \prod_{i=1,j} (1-L_i\%)I_1$. If the rural sector is sector j, then the fraction of losses from the power market to the rural market are $(O_j - I_1)/I_1 = 1/[(1-L_3\%)(1-L_2\%)\ (1-L_1\%)] = 0.35$, or 35%.

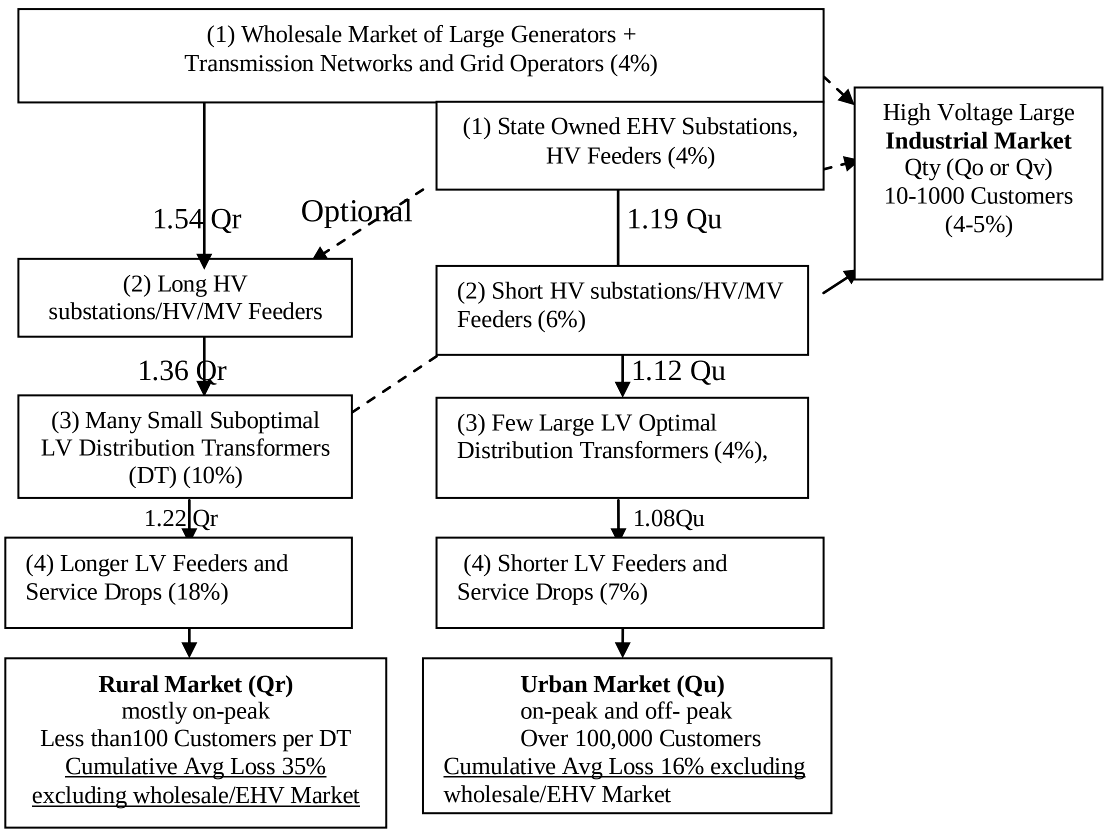

Figure 2-5 Indian Rural Electricity Market, HV and Wholesale Markets (Loss %)

The on-peak marginal energy cost in the wholesale market varies between Pw-on=10-30 c/kWh. I will use an average of 12 c/kWh based on the average real time price (Unscheduled imbalance price in the largest Indian interconnected grid) in the latest 13 months (Aug 2008-Aug

2009) of available data after creation of the Indian power exchanges.

Table 2-1 shows the amount of energy inputs at each section to get one unit at the customer meter. It also shows in the last row the percentage technical energy loss incurred in each market starting from the wholesale market. The output at rural market is denoted by r, Qr = O_{jr}= (1-0.35) I_{ir} = 0.65 I_{ir}. If the input price is Pw-on, then the price at the meter output should be Pw-on*(1/(1-0.35)) = 1.51*12 c/kWh =18.36 c/kWh to compensate for the total purchase I_{1r} = (1.54*Qr) that is required in the wholesale market.[7]

Now I show how such high rural loss can be hidden in the overall utility average loss and will be known only when the utilities run on commercial lines and try to figure out their cost seriously in each stage of the delivery chain. Assuming an equal percentage of sales in all three markets - urban, rural, and industrial - the overall average loss is only 21% as shown in Table 2.1 ((O_{1r}+O_{1u}+O_{1v}) -1)/3). If the industrial HV sales increase, the average system wide loss will be lower but if the rural sales increase as is expected from RGGVY, the average utility loss will increase.

Table 2-1 The Calculation of Cumulative Loss % at each voltage level

End-use Power Markets → Distribution Segments (Down)	**Industrial HV Load (Qv)**	**Urban LV Load (Qu)**	**Rural LV Load (Qr)**	**All Distribution Metered Load Qr+Qu+Qv**
Normalized output at customer meter reading) Oj	1.00	1.00	1.00	3.00
Input at LV secondary feeder I3 (i=3)		1.08	1.22	2.29
Input at LV transformer I2 (i=)		1.12	1.36	2.48
Input at HV transformers and Feeder I1 (i=1)	1.05	1.19	1.54	3.78
Cumulative Loss % (Oj -I1)/I1	1.05-1.00//1.05	1.19-1.00 /1.19	1.54-1.00//1.54	3.78-3.00// 3.78
= Cumulative Loss %	5%	16%	35%	21%

Source: Author's calculation based on loss assumptions in Figure 2-5

After reviewing the literature on supply and cost issues of rurality above, I next review literature on income and the true demand for electricity backed by willingness and ability to pay for the electricity. With demand and cost information, I will show that poverty can make electric grid economically non-sustainable in the long run.

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[7] This 35% loss was initially used by the World Bank in the Orissa privatization and reform plan, which was later found lower than what could be achieved (World Bank, Orissa Review, 2004).

2.2.2 Poverty: Low demand for electricity

Table 2-2 is a comparison of typical households in the USA and India showing how a demand and supply equilibrium is destined to fail in rural India, but will be commercially viable in urban areas and most everywhere in the USA. The average electricity revenue collected per customer in an Indian village is, at present, less than three dollars per month compared to more than $80 per month in the USA.

Table 2-2 Indicative rural and urban incomes and consumptions in India and USA

	Urban		**Rural**	
	USA	**India**	**USA**	**India**
Annual Income $/customer	70,000	2400	60,000	720-1200
Number of Customers/mile	35	200	7	40
Annual Revenue $/mile	42,000	24,000	7000	300-1200
Grid Upfront Cost $/per customer	2200	<500	2800	500-5000
Grid Revenue Required in $/Customer (1)	330	<75	420	60-600
Consumption kWh/Year	10,000	2000	8400	360- 1200
Tariff $/kWh	0.12	0.06	0.12	0.025-0.04
Annual Revenue $/customer	1200	120	1000	9 – 48
Needs capital subsidies? Fixed Cost > Revenue; Energy subsidies extra	No	No	No	Yes
Spent For Food/Milk	<10%	70%	<10%	90%
Spent For Electricity	<4.80%	1.13%	<2.0%	1.5%-6.40%

Source: NRECA (2008) for the USA and Author's estimate for Rural Orissa and Mumbai in 2005. (1) 15% fixed cost capital recovery factor assumes a conservative estimate of 7% financial cost, 3% depreciation, and 5% O&M costs.

The supposedly rich villagers in Eastern India today are comprised of less than 10% of all rural households and have an average income of less than $500/month. This shows they are much poorer now than an average USA household was in the 1940s, when grid electricity made its inroads into rural USA (income was about $2000/month and electricity price was above 20 c/kWh in 2008 dollars (Edison Electrical Institute 1973; Rural Electrification Administration 1982). The low Indian rural incomes and poor demand growth that limit electricity use to only a couple of lamps per household are unknown in the electricity history of developed countries like the USA. The projected average rural household income in India will likely remain at less than $300/month by 2020. This is less than $2 per day for a family of five. Thus, many poor states in the country, with much less income than the average, will continue to seek subsidies for more basic needs like food, housing, health, and water; electricity will be at the bottom of their need hierarchy. A poor economy cannot afford to provide subsidies for all these fronts. Therefore, minimizing subsidies for electricity will be helpful in contributing to better social spending on health, education, and other core rural infrastructure that will contribute to income, employment, and removal of poverty.

In order to understand how poverty creates low demand and a loss of scale economy, let us compare the Indian demand with that of the USA. The demand for rural India is very low, as shown by Dr in Figure 2-6 in the right panel. In contrast to the USA's rural household average consumption of 600-1000kWh/month shown on the left, India is at 30-100 KWh/m (EIA 2009; World Bank 2009; MOP 2005).

The Rural Grid USA (Left Panel) The Rural Grid in India (Right Panel)

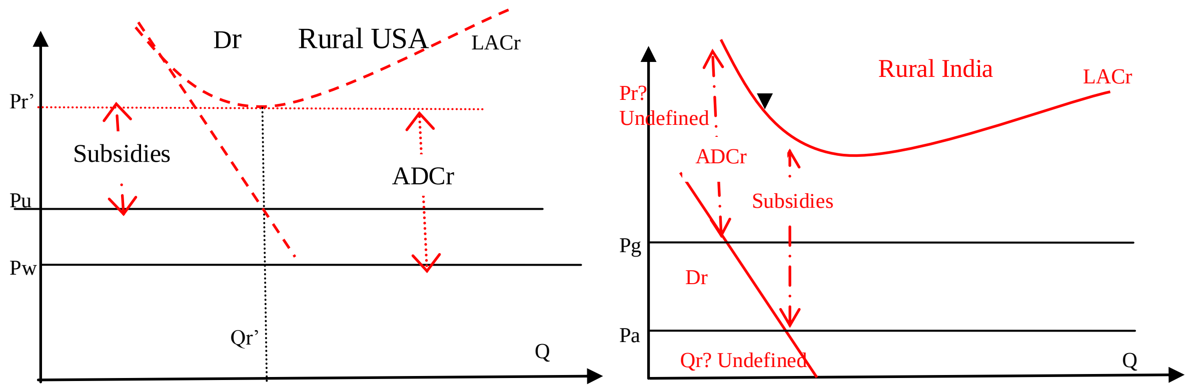

Figure 2-6 Grid Electricity Market does not Exist in Rural India
Source: Author (2009)

For rural market equilibrium and the grid's commercial sustainability, it is necessary that the demand curve is at least equal to the dashed straight line Dr (USA) so that the costs are fully recovered. In the left side panel, the rural market of the previous figure for the USA has been redrawn. The consequent equilibrium demand is Qr' and the average cost (Pr') could be at the left part of LACr without any subsidy. A small amount of subsidy can reduce the average cost of a natural monopoly and make the power affordable. This could be achieved in the USA with high incomes and a high urban to rural population mix (82/18 in 2008) requiring small rural subsidies. The rural electricity prices are the same as the urban price. Unfortunately, this equilibrium cannot be achieved in India because of low urban-to rural mixes (30/70) requiring very high subsidies that are not available from a poor economy with rural household income 1/50th the size of the USA (AEIR 2008). I will show in Chapter 5 with my data analysis that Indian demand is much lower than the cost of supply at all levels of quantity produced, as represented in Figure 2-6. Thus, an unsubsidized rural market cannot exist. The Indian rural market price Pr and quantity Qr are indeterminate due to the lack of a market (or regulatory cost equals revenue) equilibrium. Thus, the prices are set based on political considerations. Pa, the price for agricultural and poor customers, mostly in rural India, is below the short run marginal cost, making it unprofitable for utilities to expand their service. I will later model the demand and supply curves of rural Indian homes to show the need for high subsidies and the electricity market failures discussed here.

Recent policy research papers of the World Bank (Khandker et al. 2009; Barkat et al. 2002), which used over 15 years of data and an econometric model has argued that the benefits of rural electrification in Bangladesh surpass the marginal costs by more than 150%. However, my review of this study indicates that the Bangladesh rural cooperatives are run on commercial lines to serve relatively rich villagers, only if the revenue per kilometer is more than $600 per month. Thus, they are different from and more efficient than the rural electric industry in India that supply almost free power for irrigation and poor households. My study in the state of Orissa, not very far from Bangladesh and with similar economic and cultural characteristics, shows that the grid can collect only $125-$300 per month, while still leaving 50% of the poor who cannot pay the access and concurrent charge (JABA village case study in Chapter 4). This World Bank study did not refer to other off-grid renewable based electrification studies that found the economic rate of return of solar home systems above 20%, but the rural grid electrification systems unsatisfactory (World Bank 1995; 2002).

There is still one more argument in favor of grid subsidies based on international experience. In all developing countries, public policies to support electricity consumption of income-poor villagers have taken the form of various subsidies and government interventions. So the argument can be made that India should also do so. I will argue to the contrary that India instead should look at how it can avoid the rural grid subsidy paradigm. Rather it should leapfrog to new century modern technology, developing from its handicaps of rurality and poverty an efficient and competitive market as has happened in the information technology and telecom sectors. Subsidies have been provided to both the fossil fuel based grid and solar PV through international aid in Bangladesh (USAID 2005), through government budgets in Tunisia (Cecelski 2003), cross subsidies in India (GOI 1991-2009) and, not by funding, but rather by implicitly reducing the quality of services in India and South Africa (GOI 2009; South Africa Diamond Mining Journal 2008). The rural grid costs and the percent of these grid subsidies in some developing countries and in India can be seen in Table 2-3. Most countries, including India, subsidize up to 100% of the electric grid distribution costs.

Table 2-3 Subsidies in rural grid electrification

Countries	**Chile**	**South Africa**	**Tunisia**	**China**	**Philippines**	**India**	**Bangladesh**
Annual Income $ (PPP 2008)/Capita	14,950	10100	7900	6000	3300	2900	1500
Capital Cost $ /Customer	1200	1500	1500-2000	-	-	500	600
Capital Subsidy	70-90%	100%	100%	85-90%	100%	90%	100%

Source: Compiled by the Author from World Bank (2009), CIA (2008) and Other Sources

World Bank (2003) surveyed all of their electricity projects and showed that not a single rural electricity project in South Asia and Africa is recovering its capital costs. Almost 60-75% of them do not recover even the operating and maintenance costs. I have seen no international economic study in the published literature showing that, in the long-term of say 5-10 years, the rural electric grid market of any developing countries could breakeven and be subsidy free. Even today, subsidies for rural electrification in the USA are continued and are hard to remove, not because they are essential for the market to function but rather due to the inertia and lock-in of the subsidies. Such subsidies to the rural grid that once supported greater access to a modern grid might now be a barrier to the penetration of more modern renewable energy in rural USA, even though older renewable energy technologies (wind and water mills) thrived in the early part of the nineteenth century. The rural conditions that make the supply of renewables a natural match with demand are now only available where the electric grid is not available, such as in rural India. The opportunity of SPVs has been lost in other rural areas of the world such as rural USA due to the complete penetration of the fossil-grid. However, I will show that blindly copying another country's historical path might lead to a lost opportunity to leapfrog and adopt more modern and efficient technologies.

Table 2-4 Retail electricity markets charge lower industrial tariff reflecting the lower costs in 2006.

Countries	**Small Residential Rates, Pr in cents/kWh**	**Industrial/HV Rates, Pv cents/kWh**	**Difference (Pr-Pv) cents/kWh**	**Ratio (Pr/Pv)**
United States	10.4	6.2	4.0	1.69
India	4.8	8.8	(4.0)	0.55
Brazil	19.0	12.2	7.0	1.56
Chile	13.6	9.0	5.0	1.51
Mexico	10.1	9.9	0.2	1.02
South Africa#	5.9	2.2	3.7	2.70

Source: (EIA 2008) and (CEA 2009). #South Africa is not a well-functioning electricity market but still charges more rational cost reflective rates than India.

Further, all prices are much higher if the power outages, safety, and other direct damage costs are added in. Indian power quality and reliability is very poor for lack of adequate investment. Industrial customers have to invest in self-generation to compensate for the grid's shortcomings or bypass the grid with their own captive generation. This bypass explains why industrial customers might no longer be induced to cross subsidize rural and poor customers. I will show that such arguments favoring subsidies are no longer correct and that the opportunity already exists to provide subsidy free power through off-grid SPV systems. Further, the emerging opportunities of subsidy-free, efficient solar electricity in a competitive market could be the potential solution to this dominant but dysfunctional government monopoly.

To keep matters in perspective, proponents of the grid could argue that USA, Chile, Tunisia, and South Africa, are examples of successful rural electrification. However it should be kept in mind that mid-income countries typically have less than 40% of their total population in rural areas (and their rural incomes are much higher than those of rural India (5-10 times that of India and similar to that of USA when it started rural cooperatives in the 1930s). Thus, smaller levels of international aid or a lower level of total subsidies or tax/transfer can finance their rural electrification plans. Moreover, the commercial viability of their grid investment has not been demonstrated yet, despite the higher income. After all, these projects are twentieth century solutions when SPV powered CFL, LED, LCD TV, cell phone, laptop, and modern energy efficiency technologies were in their infancy or non-existent. However, we are seeking a twenty-first century solution to match the modern developments in ICET. We will also seek decentralized market based solutions but not costly, politically controlled regulation that leads to inefficiency. A market-based solution will lead to the emergence of market entrepreneurs who will innovate, reduce costs, increase values, and bring electricity consumption closer to a potential equilibrium. Instead if the subsidies and cross subsidies route to rural electrification is taken, the inefficiency, scarcity and externality costs will be hard to control as I will show next.

Lastly, all rural electrification projects like RGGVY are based on the social needs of affordable electricity. Can these needs not be satisfied by the present level of solar and biomass power technologies? In order to meet the same set of end usages, the villagers need a small quantity of high quality electricity that, I will show in the next section, might not be large enough to make the grid commercially feasible. Efficiency, conservation, the low scale of operation and the affordability of the electric grid are not natural friends of electric grid profitability. Further, without multiple players buying and selling to create a dynamic, competitive environment with transparent prices, product innovation, value creation, and efficiency cost reductions such new technologies are unlikely to evolve.

Clearly, the international agencies in their sincerity to develop rural electrification have overestimated the benefits and underestimated the grid costs without perfect knowledge of what the cost and efficiency trajectories of the modern technologies in off-grid SPVS. In the next section, I will show the anti-competitive and anti-development retrogressive policy that a grid only subsidized monopoly can encourage in the developing world. Indian grid expansion depended on international aid until the 1990s and on cross subsidies from the industrial customers after the 1990s. After 2000, it has been impossible to extract excessive monopoly rent from these ratepayers, and taxpayers have carried the large subsidy burden. A contribution of this thesis is to clearly highlight how in the name of the subsidies for the poor and for farmers to feed more than a billion people, a joint urban and rural grid has suffered from scarce capital resources and inhibited an adequate flow of funds to the urban market. I will also show how and why the Indian grid has failed even in the urban market, and it is not likely to turn around as long as the rural grid needs cross subsidies. Subsidies and cross subsidies lead to mispricing, regulatory lock-in, government control, less competition, and the lack of innovation from market forces.

2.2.3 Market inefficiency of monopoly fossil-grid perpetuate subsidized rural grid and non-technical costs

This fossil-grid system invariably shows textbook market failures of all sorts; resource scarcity, externality costs, economic inequity, monopoly, and principal agent problems with asymmetric information. We will divide our discussion of these problems into two parts, the first relates to the social costs of a monopolistic electricity industry structure and the second to the social costs from emissions. I will describe first the issues of monopoly and subsidies and then describe how the Indian grid model perpetuates itself despite its past failures to be sustainable.

Economic externality: Cost and subsidies in a monopoly market

I described the investment and operating cost drivers of the rural grid in section 2-2-1. These costs are to be recovered in the price of electricity. In a competitive market, prices for marketable goods and services are determined by total market demand, which is not determined by a single monopoly, a cartel, or government regulators. Therefore, the suppliers determine their economic costs of production and compare them with the price to see whether they can sell without any loss as no subsidies are available in competitive markets. The price reflects the short run marginal cost of the most expensive supplier in the market. Such a price convergence to the marginal cost does not occur automatically in the electricity market, as the market is not competitive on its own due to various technological constraints such as transmission, loop flow where the power cannot be directed in one direction to the intended customer cheaply without affecting other buyers and sellers. Often multiple products are sold in an electricity market: capacity, energy, transmission, and ancillary services. Even though the supposedly competitive markets in PJM/Midwest ISO/NY ISO are large, organized, and centrally dispatched, they are still closely monitored. All retail electricity markets are considered franchised monopolies and are closely regulated. In the Indian context, rural electricity markets, as explained in section 2.2.2, do not exist as such and must be highly subsidized when created to serve the rural poor and farmers.

In such a monopolistic and subsidized market, how, then, are the costs and the prices of electricity services determined? This often requires an enormous amount of planning and market forecast data as the prices or technology selections are not transparent nor can they adjust quickly, being data intensive. Additionally, this cannot be done without market regulators despite their bounded rationality, limited foresights, and often incentive incompatibility with socially optimal outcomes. (Stigler and Friedland 1962; Cohen and Stigler 1991; Joskow 20005; Cronin and Motluck 2009)

Over the last few decades, the repeated failures of India to provide adequate, affordable, and reliable electricity to its homes, farms, businesses, and industries have been subject to intense policy discussion with very little economic analysis of the negative economic impacts of the joint rural-urban markets. With a high fraction of rural customers, a market solution might be infeasible, and regulatory decision-making turns out to be subjective without the benefit of transparent price signals from a competitive market. Various solutions and regulatory fixes have been tried, such as restructuring, privatization of generation, distribution, and state and federal separation and joint planning. Often, arguments are provided by customer lobbies, local utilities, and/or state and federal governments to international aid agencies claiming that subsidies are essential and must continue. However, there is practically no literature or debate on how to create a competitive rural power market through new solar technologies to help dismantle the current subsidy regime. I will show in this subsection that there will be no immediate solutions to these problems that add both direct and indirect costs onto the Indian citizens. I will outline these problems as follows:

- Monopoly: misallocation of resources
- Regulatory failure: mispricing, elite capture, and investment mistakes
- Risks: outages, scarcity, terrorism, and natural calamity
- Environment issues: emissions and ecological disasters

Before I discuss these in turn it will be useful to review the commercial history of Indian grid industry over the past decades

A brief history of power market subsidies and cross subsidies

Though the Indian power market is monopolistic, it has been unable to recoup its high cost of rural operations as can be seen from the three related plots in Figure 2-7.

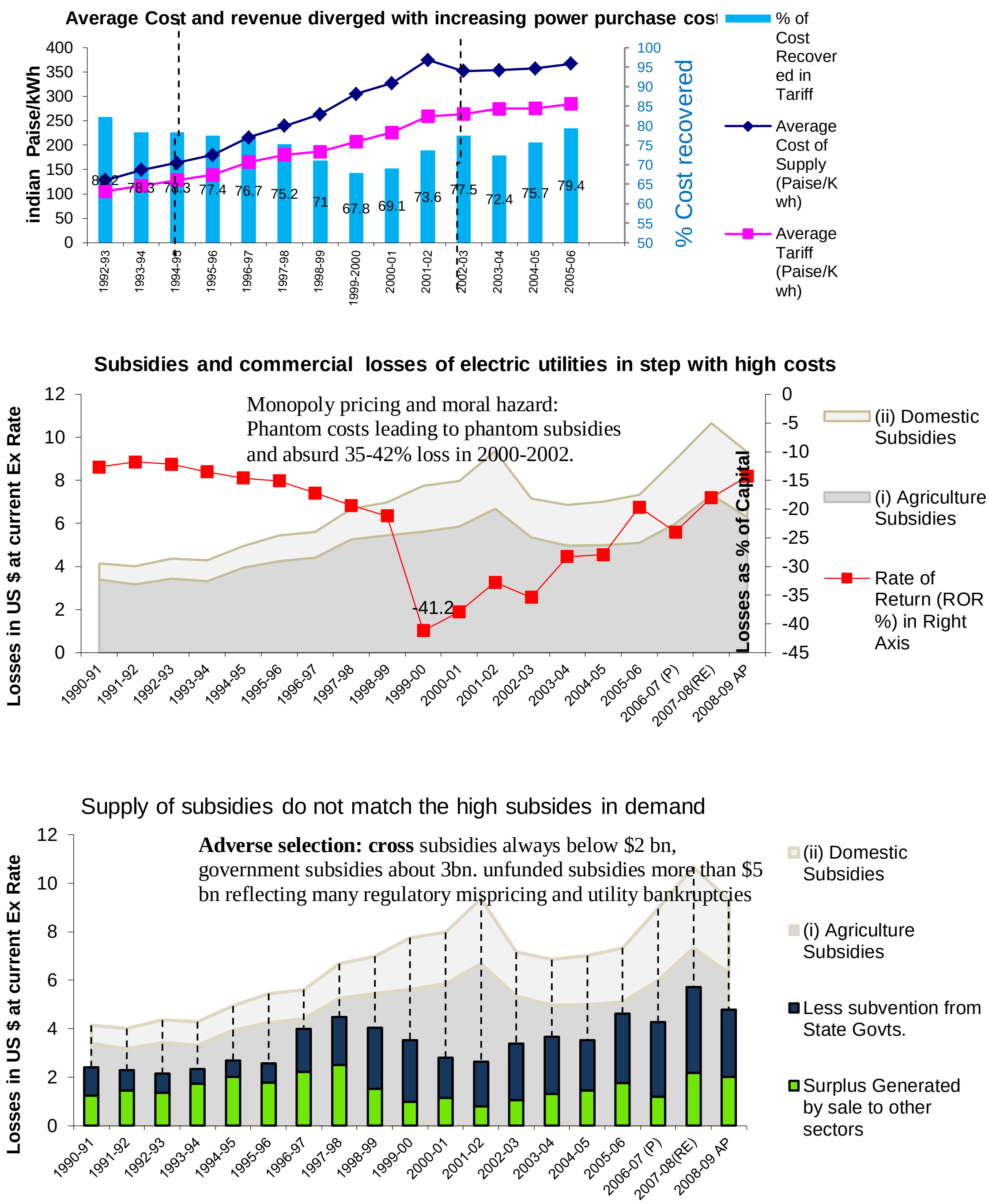

Figure 2-7 Two decades of poor financial health of Indian power sector (1990-2009)

Source: Compiled from the data of Indian Planning Commission, Central electricity authority, Ministry of Power, Economic Survey of Government of India (1990-2009)

The top panel shows the average costs of state utilities increasing at a faster rate than the average tariff/revenues. With the larger cost-revenue gap, no more than 67.8% costs are recovered in the retail market. Thus, the demand for subsidies has been increasing for farms and homes over the last two decades as shown in the middle panel. The wide gap between the source and the destination of the subsidies (thin bars) to domestic and agricultural customers is shown in the bottom panel. With the poor revenue base of rural electric utilities, the annual revenue-cost gap for all of India increased steadily from about $4 billion in the early 90s to an astounding $9 billion in 2002, hovering around the $7-11 billion level until 2009 (GOI 2009). I believe this gap in revenue, of around 1% of Indian GDP, is uncollected because of low consumer demand (incapacity or unwillingness to pay the high cost of a highly unreliable supply) discussed in the previous section.

The portion of the subsidies actually paid by the cross subsidizing industrial sector are shown in the bottom panel as green bars and the direct subsidies paid by the government as the black bars above the green. Together, the funding on these subsidies are only half of the total subsidies demand and the shortfalls are as shown by the dashed lines compared to the total subsidies shown in the grey area plots in the background. Excessive subsidies of around $10 billion dollars were accompanied by the decreasing cross subsidies from 1997-2002. I argue that these are the results of an arbitrary wholesale pricing mechanism with no regard for the retail market absorption capacity. This situation with controlled retail prices below costs is not so different from the California electricity market debacle of the same period.

1. Market inefficiency of monopoly regulation:

The failure of the power sector for many decades occurred because of monopolistic industry structure that requires regulation. Incompetence and lack of foresight often led to regulatory failures with no attention to what the market could bear and the reality of the poor customer base. The high rural agricultural load, which is now consuming 22-26% of total electricity in the country, is heavily subsidized on the political grounds of needed food production. The cost plus power contracts and regulatory pricing at the highest federal level on the supply side bleeds the rural utilities of the cash flow to operate and maintain a viable electric grid business. The resulting commercial losses that have reached more than 40% as shown by the red line plot in the middle panel of Figure 2-7 yield a negative return on assets.

This study will find a solution to the above problems. It will show that a competitive SPV market can evolve to solve the core issues of pricing, subsidies, and incentive incompatibility of regulators with social welfare. Fringe renewables like SPVs in rural areas will help to create this competitive market and promote rural development.

2. Regulatory failures of mispricing, elite capture and investment mistakes

I will briefly mention two well-known, non-technical costs of regulatory failures, not because I deal with them directly, but because they are costs that deter the growth of an efficient, competitive market. They are moral hazard, adverse selection and elite capture, which have long-term effects on societal behavior and expectations, the government's capability to attract capital investment, and the skill set necessary to meet the social need for more investment in both rural and urban areas.

Moral hazards and adverse selection are two economic costs that result from asymmetric information between the two contracting parties leading to behavior incompatible with economic efficiency. Moral hazard occurs when the party with more information can shift risks to the one with less information. Adverse selection occurs when the wrong selection takes place as the principal does not know or cannot discriminate between a good and bad agent. Elite capture happens when only a few rich and politically connected households get access to the fossil-grid system. I will describe some evidence of these market distortions in the Indian power sector below. This will prove my argument that the Indian regulatory framework is not efficient enough to mimic a competitive and efficient market where grid electricity pricing reflects its true economic costs.

a. Moral hazards:

There is an apparent hope that the Indian government can electrify all rural households by 2012 under the top-down government program funded with taxpayer money. A predominantly rural and poor India is yet to electrify over 80 million rural households. Thus electrifying just 2 million households per year at its peak in last decade with dubious quality power supply is likely to leave 50% of households electrified for decades to come even after the $13 billion upfront investment (Srivastava 2009; Cust et al. 2007). The household electricity subsidies already add up to the already high agricultural subsidies. The combined burden will tax the productive sector as cross subsidies, which will lead to increased bypass of grid electricity, in particular, and to the loss of economic efficiency and growth in general.

All these non-technical costs might be over shadowing the true technical costs of the Indian grid in total. The true costs of the rural grid, due to the joint administration of the urban and rural markets, are not transparent in India. There is no separate accounting system to track the true costs of the rural grid. The unfunded subsidies encourage poor maintenance of equipment and lower life span of the power system (25 years or lower, internationally these are 35-40 years).

In this precarious grid supply situation, a standalone subsidy free off-grid rural SPV market will relieve the urban electricity supply from the rural cross subsidies burden. To make grid costs comparable in a competitive market to SPVs, I will assume 25 years of useful life, a 4% depreciation rate, and 14% cost of capital. These assumptions reflect the returns on capital employed and the nominal rates CERC adopted for generation projects during 2008. When more than 50% of subsidies are not funded by the cross-subsidizing ratepayers or tax payers, it should be obvious that the shareholders bear these costs. Therefore the 16-25% return on equity should not be considered the true expected return on equity from electricity investment but rather an administrative desired/nominal return. The long-run expected return on investment that the Indian government and public power equity holders can expect to get is close to zero or negative rather than the economic cost of capital in the broader market. Since the government cannot get funding at 0% return, it will ultimately tax the public to raise money to compensate for the poor return of the electricity projects and continue to expand and maintain electricity assets at a 14% nominal cost of capital (CoC) that is probably appropriate. In a competitive market where an SPV business can thrive at a 14% CoC, there will be little justification to allow a grid supplier more than 14%. Therefore, I will assume 14% CoC for both technologies.

Taxes are omitted from my analysis because they are a transfer.

b. Adverse selection

The opaque pricing, urban-rural joint management, and complex grid regulation create the demand for transfer and subsidies by the various class of users: for farmers to feed the nation, to provide a reasonable lifestyle for the poor, for urban mass consumers to avoid protests in the highly visible capital cities, and for industries to promote economic development. These demands for subsidies face a lack of government tax revenue or of highly profitable businesses able to provide cross subsidies. The result is adverse selection, grid bypass, continued subsidy needs and uneconomic grid expansions that we will discuss briefly here. Some of the following adverse selection results from the lack of current and future information on grid cost and demand, high cost of gathering information and inherent asymmetry of information in the long rural grid supply chain.

- Power, coal, and equipment suppliers as well as customers choose wrong technologies because of inappropriate price signals.

- Poor customers and farmers: some may not pay bills, some receive free power leading to unproductive use of scarce water and electricity as discussed earlier
- Middle class: some not willing to pay, elite capture, stealing 20-30% in urban areas
- Large businesses and industries: can litigate, bypass, or self-generate
- Unmetered supply and highly subsidized electricity to farms and the poor also lead to gaming by the utility managers to engage in activities to hide the costs of the cross subsidizing sector as high costs of the subsidized sector. This, to my knowledge, is a primary driver of high declared subsidies shown in the power sector. The low paying customers are allocated most of the costs to easily hide the mismanagement.
- The urban and rural joint ownership is one such source of cross subsidies and results in inefficiencies, lack of information and adverse selection in sharing the cost responsibilities.

Rural and urban joint management with opaque accounting does not encourage true cost discovery, but creates an opportunity for gaming cost allocations across various consumer classes through the control and ownership of a dominant grid firm intentionally designed as a joint urban and rural market. Various state governments desperately tried to balance the high cost budget by increasing revenue through administratively determined high prices for industrial customers. The very low price to rural farms and homes could not be increased without political repercussion. Such high pricing in the range of 8-18 cents/kWh, as seen from government data (CEA 2009) for industrial customers without a guarantee of better quality of power, neither support economic growth nor electricity revenue growth due to demand destruction and industries bypassing the system. Moreover, the large industries can produce their own power at 4-5 cents/kWh from auto generated coal plants and small commercial centers, using subsidized diesel fuel for generating power below the utilities costs, so why should they buy from the state utility firms (IEA 2002; Seetha 2009). Thus, the joint urban and rural grid has nearly lost dominance in the lucrative industrial markets and cannot make up lost revenue through cross subsidies. The current amendment in the electricity supply act will allow more such bypasses and make it virtually impossible to collect cross subsidies for the rural sectors. The true cost of the cross subsidies on the wider economy is hard to calculate and will not be attempted in this thesis. However, the subsidies are unavoidable in a grid-electricity paradigm of rural development with so many poor population seeking to catch up with the urban world driven by electricity. The argument is often given that, internationally, the rural grid is subsidized, and as there are no other cheaper off-grid self-sustaining commercial solutions, such cross subsidies must continue.

Although computing all these non-technical costs related to moral hazards and adverse selection is complex, they have a wider impact on the economy. Although they are beyond the scope of this thesis, I believe they continue to be a significant portion of the costs in the Indian electricity grid today and will remain so in future as long as the urban to rural cross subsidies continue. There is a gap in literature in this regard, and the Indian power sector could provide ample data for a more in-depth study of adverse selection in a regulated power market. With the knowledge of the costs of such faulty regulation needs to be spread widely so mistakes are not repeated. The apparent possibility of such adverse selection in the future in the Indian grid further bolsters my arguments in favor of off-grid renewables to make the rural grid not only subsidy free but disentangle it from the urban grid, which has no need or justification for subsidies.

c. Elite capture:

Indian electricity supply provides a classic example of "elite capture" where highly subsidized electricity reaches only half of the population and mostly rich people derive the direct and indirect benefits of both electricity and the related subsidies. The poor are the passive sufferers of the externality costs with few benefits of electricity. This inequity can lead to diverse social problems including terrorism, migration, crimes, stress on civic amenities, and public health issues, all of which are externality costs not reflected in the prices of the fossil-electric grid. The Nobel Peace Award to the micro finance guru Md. Yunus to improve the lives of the poor reflects this thinking that economic equity should be an economic goal. If this goal can be achieved through a large number of privately owned and operated competitive markets, such externalities will not occur. My thesis will investigate the possibility through off-grid renewables, which is also very popular in Yunus' fight against rural energy poverty through the competitive market, run by the poor themselves.

d. Inappropriate, untimely investments

The discussion above indicates that the rural grid has been inefficient, insufficient, and I will show it is unnecessary. Figure 2-8 demonstrates how from the 1990s to the early 2000s when China, South Africa, and middle income countries were rapidly expanding their grid for a lack of competitive alternatives like SPVS, India was in deep trouble trying to operate utilities and raise investment capital. Rural electrification came to grinding halt. What is not shown in this figure is the fact that more than 100,000 villages have been de-electrified or wrongly indicated as having been electrified (MOP 2005). More than 80 million households, almost 56% of the total, remained out of the fossil-grid system by 2005.[8] The electrification that jump started from 2006

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[8] The subsidized irrigation pumps continued all these years in a few rich states creating more issues of water depletion. Poor quality of power supply requires over-sized pumps to extract as much water as possible during the few hours supply increasing the inefficiency and costs of the farmers and the grid suppliers. Low market prices of water intensive

also could be untimely, too late, too expensive, and inappropriate. Any aggressive subsidized rural grid electrification will obstruct a potential competitive power market with predatory pricing precisely when the modern SPV technology and efficiency have appeared as the competitive alternatives. These alternatives, I will show in this thesis, need promotion not the rural grid. The power sector has not improved in the last two decades of reform in India. Any government guarantees for investments by the World Bank, IPPs, federal power companies, and state utilities for nonfunctioning grid improvements are a diversion of public funds from more useful social and infrastructure development to the power sector. It is essential that such public money be used to guarantee the success of energy projects that reduce the dependence on future subsidies not on a trial and error solution to a system that demands more subsidies later.

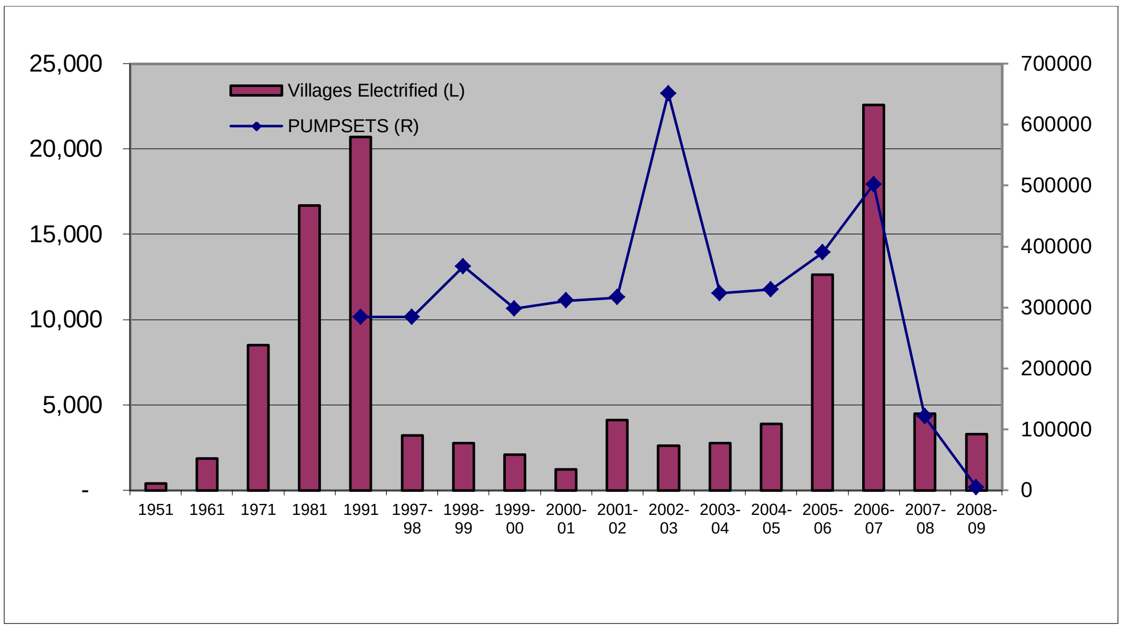

Figure 2-8 Indian rural electrification priming up after lost years of 1991-2005
Source: GOI 2009: Doing more of the same rural grid in the 21st century when alternatives are better. Left and right represented as (L) and (R) respectively in the legend.

3. Energy risks: Scarcity, outages, terrorism, and natural calamities

a. Scarcity of fuel and water:

The dependence on fossil fuels has recently been examined as too risky to let the consumption decision be made on short-term market forces alone. Even the long term energy

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rice production lead to poor profitability and the need for more subsidies to farmers. The large electricity subsidies partly compensate for the less remunerative food production. Such use of scarce water, land, and water resources needs to change to more profitable and less water demanding vegetables and other crops suitable for the rural land endowments (USAID, 2005).

market does not exist or behave rationally from lack of enough foresight. Fossil fuel prices increased from 2004-2008 to previously unknown heights as did the prices of other basic commodities like steel, cement, metals and silicon (EIA 2009). Such price fluctuations increase the risk of fossil fuel generation. Their potential returns as the world economy recovers have the potential to drive up long run average costs of the entire fossil-grid. The Indian government has now realized the acute shortage of coal as the main primary fuel after the year 2030, when the coal production will most likely reach its peak (CMPDI 2001). Similar water scarcity and nuclear fuel scarcity are also prominent in India.

b. Scarcity of electricity and power outage:

The energy shortage at 7-20% shows that the country has not been able to meet the needs of the customers already connected to the grid. Therefore, it could be expected that if the grid condition had been better, the suppressed demand would have appeared as additional load in the power sector as well as increased economic activities, jobs, and incomes in urban areas. Thus, not only is grid power inadequate, unreliable, and expensive for the current consumers, but the Indian industry and business potential also remain largely untapped. The black-outs, brown-outs, and lack of access are likely to continue for years to come as the core issue of minimizing subsidies as well as financing these subsidies have not been addressed.

In order to support the manufacturing industry, the government (NMCC 2006) estimates that the average manufacturer in India loses 8.4 percent a year in sales due to power outages as opposed to less than 2 per cent in China and Brazil. World Bank (2004b) estimates that Indian manufacturers lose 9% of total output and face 17 significant power outages per month verses one outage in Malaysia and five in China. A very recent study by Wartsila (2009) found a 6% loss in GDP for the entire economy from electricity outages. The economic loss due to the failure of the electricity industry in rural and urban areas retards growth everywhere. The Powergrid corporation calculates that the value of lost load to the India economy is Rs. 34-114/kWh ($0.75 - 2.25/kWh) that translates to more than a 60 billion USD loss to the economy (Wartsila 2009). MAIT (2008) shows the loss of production at much higher levels for manufacturers, at around 10 billion USD and claims that 95% of IT firms in India use off-grid distributed generators and battery and inverter systems. Basant et al. (2006) shows a very high return of Information and Communications Technology (ICT) on productivity in the Indian and Brazilian manufacturing industry on a survey of about 476 Indian firms and about 500 Brazilian firms during 2001-2005. They found several constraints to ICT investment in both countries but power disruption seems to significantly depress adoption and returns to ICT expenditures in India. The power supply problems in India was quite high at nearly 22 days on average for the industries surveyed against no such reported problems in Brazil. They also reported that not only do firms in more power-disrupted states in northern and eastern states invest less in ICT, they also get a lower return from their investments in ICT.

The greater use of fossil fuels, especially when converted to electricity, improves public safety, creates new technologies, and advances modern communities with better health, education, lifestyle and productivity not seen in earlier civilizations without the electricity. But these benefits, if they do not extend to remote parts of a nation or to different parts of another country can create economic inequity (UNDP 2002; WDR 2006). Further, to prepare themselves for the risks of disruption and power quality issues, customers in India routinely invest in battery based systems. These battery operated devices and tools, which cost more than 1 % of the GDP, will not be included in our model but will be noted as energy externalities (MAIT 2008; Wartsila 2009).

c. Terrorism and natural calamities:

Recently terrorism and cyber security concerns have added vulnerabilities of the centralized automated grid operation practices. Natural calamities such as storms, earthquakes, flooding, and excessive rain/snow/wind/heat all have additional unanticipated costs that no utility or consumer can predict accurately (Bradley 2005). The insurance cost for some of these is likely to increase with the global warming concerns.

4. Emission and ecological damages

First, the literature on the emissions and local pollution from fossil energy is well established with all countries now taking elaborate steps to internalize these costs through environmental regulations and technological mandates (Flue Gas Desulphurizer (FGD), Super Critical Boiler (SCB), fish screens in cooling water systems, Electrostatic Precipitator (ESP), and chimney heights), or pollution credits (sulfur pollution rights), or by restricting operations of older plants (grandfathering only for certain ages). Acid rain, water and solid waste, ash, haze, mercury, ozone, noise, fumes, and aesthetics are all regulated, but negative externalities are not completely removed. Economists argue that such regulation should only extend until the marginal damage costs are equal to the marginal costs of abatement. Many developed countries can afford to invest more in pollution control and have a low level of social tolerance for pollution. Thus all pollutants that have immediate health, visual, or sensory impacts are immediately controlled until the river, air, and vegetation are clean, noise and smoke free with disease causing actions by the industry immediately penalized. The environmental lobby, litigation, and an alert government all work hard in a thriving democracy to see that these externalities are internalized to a level that society will accept.

The government owned polluting fossil-grid industry in developing countries is not penalized as severely for breaking the rules as are private players of developed countries. Such emission and pollution related externalities might reduce the fossil-grid costs but cause social harm to the poor who do not participate in either production or consumption. As a very clear example, the eastern Indian states produce most of the coal and coal-based electricity suffer from the related pollution, loss of flora and fauna and involuntary displacements but are the least electrified in the country. Though we will not add these costs in our model, their avoidance will be an added advantage of renewables.

Second, the global emissions of carbon have caught the attention of the world and created intense heat in academic, political and civil society literature. The latest reports of the ICCP (2005; 2007; 2008) under the UN and actions of oil companies like Exxon Mobil (Bell 2007) have brought finality to this debate. The U. S. National Science Foundation and White House as well as other coal-using skeptics such as Australia ultimately are acknowledging this reality through political means. The fossil-grid system is the largest single source of the climate changing gases and is now the primary target for regulation through cap and trade or carbon pricing. The subject matter is fluid at this time and will unfold in the next few years. We will not include these costs of carbon in our cost model but indicate this as a possible funding option that will make the rural un-electrified homes and businesses the target of an efficient and renewable based clean development mechanism (CDM) as effective carbon sink.

One of the main reasons for world's recent effort to adopt renewable energy on a large scale is the intention to internalize the externality costs of pollution, resource scarcity and price volatility of fossil fuels. Though such a model is making a dent in developing countries like India with recent active support of Greenpeace and the Indian Ministry of New and Renewable Energy (MNRE), I will later argue that an off-grid framework will address both the internal and externality cost issues together while the renewable grid addresses only the emission issues.

The arguments of local emission and global climate changes are required to justify renewables in the urban grid. Similar logic will not sound convincing to development economists or illiterate villagers in provision of power and all of them have supported some form of the fossil fuel and electricity subsidies to the rural poor. Unlike in western countries, the rural poor will not be willing to pay more and the Dr curve will not move upward to buy the clean and renewable electricity. They will hardly understand such concept with their poor knowledge and education. There is also the possibility that self-sufficient rural energy will avoid the risks of remote fossil-grid electricity.

The costs of pollution have been computed by many authorities and I will not discuss them in the context of India except for a brief summary Table 2-5 below gathered for the USA. My later results will show that rural Indian grid costs are already higher than SPV power costs without adding these externalities.

Table 2-5 Social cost of the USA grid: Pollution, politics and friction

Energy Technology	**Source of Externality Costs**	**Amount/Nature of these costs**	**External Parties who pay**
Renewables SPV/Wind/Biogas/Biomass	Environment Cost	0-0.7 cents/KWh	Community
	R&D Cost	< $1 Bn	Tax Payers
Coal	Environmental Cost	3.3-6.8 cents/KWh	Community
	Clean Coal R&D	NA	Tax payers
Natural Gas	Environmental Cost	0.8-1.2 cents/KWh	Community
	Scarcity	NA. Price volatility	Future consumers
Nuclear	Environmental Cost	2.91 cents/KWh	Community
	R&D Cost/Other	Insurance cost by government	Tax payers
Oil	Environmental Cost	3.0-7.9cents/KWh	Community
	External and Internal Security	Security forces >$40 billion	Tax payers
	Intangible Cost	Reputation at stake	Community
Grid Electricity (added by Author)	R&D Cost	Government	Tax//rate payers
	Rural Coop Subsidy	State//Federal budgets	Tax
	Regulation Cost used for lobbying or fighting legal battle	Cost incurred by congress, regulatory agencies, and government to legislate and administer numerous laws. Efficiency loss in misused human capital, policing a complex grid system	Rate payers/tax payers Many of these costs are not in present rates. In advanced countries tax payers are rate payers, but in underdeveloped countries tax payers are very few.

Source: The table here indicates in US cents/kWh the environmental cost study done by the Pace University Center (1991) for Environmental Legal Studies during 1990-91. More recent costs show the damage costs in a similar range.

One of these too little, too late projects is the highly expensive rural investment program, RGGVY. It is based on the subsidized fossil-grid paradigm without looking at the cost, demand, and reliability of this power to rural customers. Though village electrification has been accelerated from 2005, I believe these subsidies to the nonfunctioning rural grid will require subsidies to kerosene and diesel with higher emission and ecological costs when cleaner and more cost competitive off-grid SPVs are emerging.

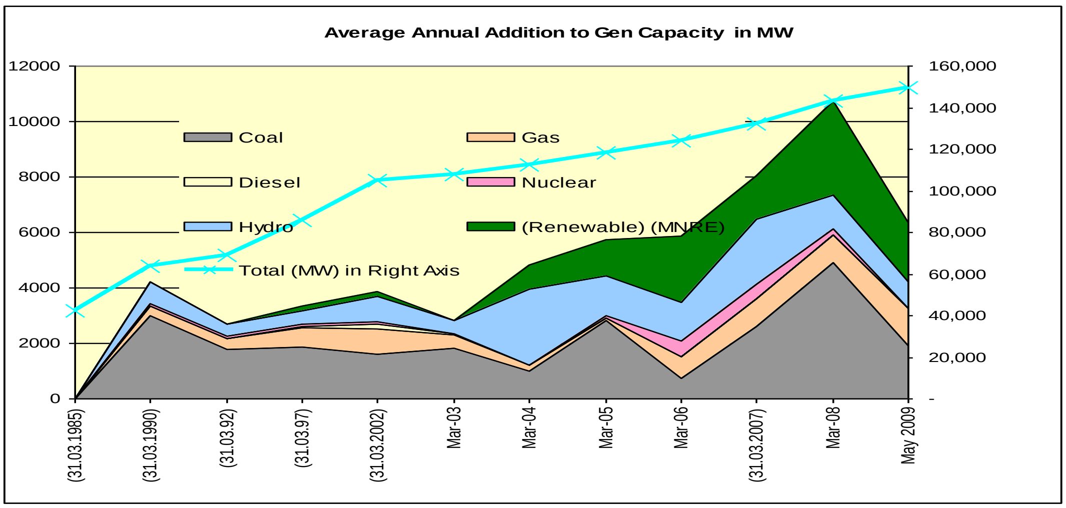

Figure 2-9 Average annual grid capacity additions in India with renewables in green (mostly wind generation)

Second is the "Renewable Grid," which depends on the grid to deliver rural renewable wind, SPVs, and biomass power to urban and rural areas through an extensive grid network. Figure 2-9 above shows that wind generation has ramped up in India through the private sector, and the annual generation addition is above 2000 MW per year from 2008. Very recently, in 2010, Indian government has introduced a national solar mission to add 20,000 MW of SPVs, mostly through the grid with the apparent hope of reducing their costs through high subsidies and mass production. Though wind generation is being subsidized, the subsidies for wind are not as high as the subsidies required for an SPV-grid, which is more expensive than wind by a factor of 3-10 (Table 2-5 of the next section). The simultaneous introduction of the SPV-grid under the solar mission and the rural grid under RGGVY, both heavily subsidized schemes, are likely to create a massive drain of financial resources compared to the off-grid SPVs that I will argue can be subsidy-free but are still being ignored. This is a core argument as well as an important and timely contribution of this thesis. Can a renewable grid solve these rural grid problems and can the government or a large private monopoly meet these needs of rural electricity in the next ten years without subsidies. In the next section, I will show from the literature review that the renewable grid cannot achieve a competitive market but rather compounds the subsidy problems. In section 2-4, I will show that the off-grid SPVs can possibly do so with their greater economic potential under a free, open and completely subsidy free business environment.

2.3 Renewable-Grid Paradigm

There are three different types of renewable fringe in the electricity market: grid-connected, mini-grid, and off-grid renewables. I will show in the next three subsections how grid-based renewables, though very popular in developed countries, are not appropriate for India for the same reasons that the fossil-grid paradigm does not work: rurality, poverty, and monopoly grid inefficiencies. In the following subsection, I will explain that though the mini-grid has some potential, it is still not yet ripe for low skill villages. The next section will deal with off-grid renewables that have the best potential for electrifying poor communities even now and more so in the future.

The literature on renewables, fed through the central grid, is briefly described in this section to show their three main justifications in developed nations like the USA. First, the classic historical grid based path dependent electricity growth in the USA or other urbanized developed nations locks out off-grid solutions. The off-grid solutions need battery support and the large consumption of these countries cannot be provided inexpensively. The urban communities also do not need portable off-grid SPV systems as much as a rural Indian household does, which I will show later. Second, the USA now is ready to internalize the externality costs of the fossil system by renewing the grid with wind, solar, geo-thermal, and bio power. The literature is split between arguments in favor of and against clean energy and higher energy costs, which are often justified from the carbon emission and global warming point of view. Finally, this renewable-grid is important for transferring rural renewable energy to urban centers where more than 80% of the USA population lives, unlike in India where 70% of the population (700 million people are more than twice the population of the entire USA) still lives in rural areas. However, I will show briefly in the following section that porting such a renewable-grid paradigm to India will lead to higher costs without providing the competitive solution for poor rural areas that is urgently required.

2.3.1 Rurality: Renewable-grid will increase rural grid costs

The renewable grid technology essentially is the same as shown in Figure 2-2 for the fossil grid with respect to geographical spread of large centralized generators. The only differences are that fossil generation is gradually replaced by renewable resources, which are more remote and spread out, less flexible and less safe to operate in the grid environment requiring more back up support from natural gas or oil or yet to be developed large scale battery systems. They also require more engineering redesign and protection systems and processes to address safety issues.

The modern renewables that are getting competitive in the wholesale markets are wind, geothermal, biomass, and large solar thermal power plants in sunny regions. The popular methods in the USA and EU to integrate high cost renewables like biogas, solar PV, and biomass power to the grid are through investment tax credits (ITC) and production tax credits (PTC), quantitative mandates on utilities called renewable portfolio standards (RPS), mandatory advanced SPV feed in tariffs (FiTs), where the utilities are mandated to buy the solar electricity at a high rate and a relatively small portion is procured through voluntary market based rates called "green pricing. In Europe, the FiT's price is typically dictated by the government's chosen technology with a regulatory mandated premium price ranging from 25-70 c/kWh (www.pvtech.org. Sept 2009). Thus FiT for the renewable-grid has a cost over and above the existing fossil-grid technology with a cost comparison shown in Table 2-6. These additional cost burdens can't be borne by the financially unviable Indian utilities and would, thus, ultimately fall on society in general, along with HV and urban customers through cross subsidies.

From Table 2-6, off-grid SPV costs are 50-80 euro cents per kWh making them very close to or cheaper than the rural grid costs in sunny lower latitude locations, but much more expensive than all other forms of renewable energy. Wind is becoming very competitive with the fossil-grid without most of the externality costs of the later. However, it needs a very well-functioning grid network with a large amount of flexible quick acting gas or oil fossil-grid generating systems to fill in for the wind's intermittencies.

As the developed countries have already locked into a huge quantity of good quality grid electricity, they have also found a path dependent (North 1990) solution to introduce SPVs into the grid through the same regulatory approach applicable to the fossil-grid. Developed countries have more or less solved the monopoly and access issues through meticulous regulation for SPVs and other renewables (instead of a real market). Now that they are accepting global climate issues, they have begun to tackle the remaining negative externalities of fossil fuels by renewing the fossil-grid system with an SPV energy based grid. Such internalization of externality costs is required for proper market pricing, but it is not enough for a transition to a competitive market.

Table 2-6 Supply costs of grid vs. renewables: Current and expected trends, Source: from Owen (2004) and ICCEPT (2002)

Energy Source	Technology	Current cost (euro c/kWh)	Expected future costs beyond 2020 as technology matures (euro c/kWh)
Coal	Grid supply (generation only)	3-5	Capital costs to decline slightly with technical progress. This may be offset by increases in the (.real) price of fossil fuels
Gas	Combined cycle (generation only)	2-4	
Delivered Grid Electricity from Fossil Fuels	Off-peak	2-3	
	Peak	15-25	
	Average	8-10	
	Rural electrification	25-80	
Nuclear		4-6	3-5
Solar Thermal	Thermal electricity (annual insolation of 2500kWh/m2)	12-18	4-10
Solar PV	Grid connected photovoltaic (annual electrical output)		
	Annual l000kWh per kW (e.g., UK)	50-80	~8
	Annual 1500kWh per kW (e.g., Southern Europe)	30-50	~5
	Annual 2500kWh per kW (e.g., lower latitude countries)	20-40	~ 4
Geothermal	Electricity	2-10	1-8
	Heat	0.5-5.0	0.5-5.0
Wind	Onshore	3-5	2-3
	Offshore	6-10	2-5
Marine	Tidal barrage (e.g. proposed River Severn Barrage)	12	12
	Tidal stream	8-15	8-15
	Wave	8-20	5-7
Biomass	Electricity	5-15	4-10
	Heat	1-5	1-5
Bio-fuels	Ethanol (petrol & diesel)	3-9 (1.5-2.2)	2-4 (1.5-2.2)
Hydro	Large scale	2-8	2-8
	Small scale	4-10	3-10

Integration of over 220 GW in wind, which is abundant in the Midwest but is required for consumption in the East, requires an increase in grid capacity. Such an increase is estimated to cost more than $80 billion, in addition to the capital investments in wind turbines, ancillary services, storage, and smart grid assets (FERC 2008, JCSP 2008, and AWEA 2007). The uncertainty of wind energy requires an expensive forecasting technology from minute to minute and flexibility in transmission design and operation that is not available now.

As gradually cheaper and abundant wind resources are exploited, remaining wind resources will have higher generation costs unless technological capabilities surpass the resource handicaps.

These grid based actions of the USA to move power from rural to urban centers are going to add to the complexity of grid regulation and increase grid costs. Nevertheless, a determined political climate, an urban and wealthy customer base, and a changing consumer preference for green energy might change the fossil-grid system to a renewable-grid system in due course; however, it will be difficult to imitate this in India because of the high cost.

The cost reduction that is possible with learning by doing or involving a large number of small market players such as customer participation in cleaning, aligning, securing and providing land, rural distributors and assemblers participating in a competitive market, increasing their skill and income, cannot be achieved in a renewable grid paradigm. Rather in the under-designed and poorly operated Indian electric grid, any transfer of power from rural areas to the central grid will require huge costs of not only grid reinforcement, but also acquisition of scarce land and related security arrangements in a crowded country side. The rooftop grid connected systems might not have these land problems, but the poor quality, downtime, and safety of the grid will require elaborate and costly interconnection security and battery support to make such an SPV-grid useful. In essence, an SPV-grid is more expensive than the fossil-grid. This additional layer of cost is not sustainable for the rural poor.

2.3.2 Poverty: Requires small-scale affordable but reliable electricity systems

The objective of the renewable-grid in the USA is neither to meet the energy needs of the poor nor to modernize a primitive village society. Mass poverty in a rural society does not exist in the USA, nor is there a lack of cheap electricity. More recently, the Indian government has shown a greater interest in providing subsidies to grid connected SPVs (MNRE 2006; 2010). India has had rapid penetration of such grid-based wind in many states like Tamil Nadu, Maharashtra, and Gujarat, driven by tax breaks and feed in tariffs. This is the fastest growing segment of electricity in India, passing the total generation from nuclear in 2007 (CEA 2007b). Greenpeace India seems to be active in promoting these green energy efforts through this renewable grid framework in their pleadings with state electricity regulatory commissions rather than through the off-grid systems considered more suitable for India in this thesis (OERC 2005). Greenpeace (Radford, 2009) has challenged the World Bank for not doing enough to promote renewable energy.[9] These environmental organizations argue that there is insufficient funding for SPVs from the World Bank. These arguments can be turned against environmental organizations to the extent that they give inappropriate attention and advice to grid-based SPVs when the massive poverty, rurality,

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[9]My analysis of the World Bank and ADB (1995, 2009) investment supports increasing attention to the urban grid and urban poor where the return on their investment can be immediately justified.

and electricity market inefficiencies in India need an off-grid SPV solution. They are supporting a grid based SPV solution that requires a very expensive complex transmission grid and may not reach the rural poor. They will be locked into a dysfunctional grid, where a massive amount of energy (20-40%) is drained out as electrical and commercial losses in poorly governed systems.

2.3.3 Inefficiency and monopoly: Renewable grid will need higher rural subsidies

The Indian utilities are inefficient, lack competitive spirit, and they possess an outdated grid technology that perpetuates electricity market failures as well as regulatory failures. When utilities require such a high fraction of energy, what good will it serve to feed SPV energy into this loss prone line while paying double the price. The SPV suppliers have already lined up for the urban SPV-grid as can be seen in the CERC document where they have been allowed more liberal norms with 20 year higher feed in tariffs for grid-connected SPVs. The existing push for the SPV-grid, as argued in the developed nations for internalization of the fossil fuel externality costs in the grid framework, can harm poor economies by not taking advantage of the much higher social welfare gain that (I will show in the next section) can be harnessed by a similar market push in off-grid SPVs. Porting these developed countries' renewable grid model, which might fit their well-functioning electrically efficient grid network with less than 10% electrical losses and virtually non-existent interruptions, will not help the poorly functioning Indian grid. The moral hazard, the adverse selection, and the grid energy scarcity for the rural poor will not be addressed. The trade-off of savings from the reduced emission and ecological damages need to be weighed against energy and economic equalities and the lack of a competitive market. Ultimately, rural energy problems will not be solved with higher subsidies to renewable generators for the grid. Rather such subsidies will preempt rural development expenditure if government expenditure needs to be controlled without spiraling inflation through deficit financing.

Although the fossil–grid system does not promise a bright future for rural India, the renewable grid is being touted worldwide as fringe electricity with Greenpeace, MNRE, and CERC, promoting this in developing India. Perhaps learning from past mistakes has been difficult in India. Like any other regulatory agencies with short organizational memory or principal agent problems, India offered arbitrarily high returns to promote a private fossil-grid system and only to fail and revert to a government monopoly. Innovation and opportunities of the rural market through off-grid SPVs and biomass power are as difficult to be seen by a large government as by the large profit-seeking capitalists.

I qualitatively examined here how a renewable grid is inappropriate or imprudent for rural India. I will show the quantitative cost implication of an SPV-grid to India in Chapter 6 after deriving the grid and SPV electricity costs and demands in Chapter 5. I next turn to the renewable mini-grid option.

2.3.4 Renewables in decentralized mini-grid systems not ripe yet for rural poor in developing countries

Mini-grids are small, isolated grids that meet the needs of a village or community with local and decentralized generation from diesel or renewables like mini/micro hydro, wind, biomass or SPV plants. The mini/micro grid enables optimal utilization of the generation resources by taking advantage of the grid customers' diversity in use and reducing the size of the generators and battery back-ups. The other positive aspects of the mini-grid is that transmission and fossil fuel use is minimized, rural resources are used, and rural people are trained to take care of energy production in an environment friendly manner.

In India, most of the rural village electrification has been promoted under the mini-grid system; very recent literature, Nouni et al. (2008) and World Bank (2007) provides a glimpse of their cost competitiveness with the grid. Nouni et al.'s (2008) analysis supports renewable energy based on village micro grids but with the restriction that they are not economic near the grid (within 5.8-25 kilometers depending on whether the terrain is flat or hilly). This agrees with the stipulation by MOP (2008) that such renewable projects have to be far away from the existing grid to receive a capital grant under RGGVY.

This is, however, a top-down plan based on high upfront subsidies and with the expectation that the subsidies of future expansion or maintenance will continue to be paid by the government. Nouni et al. did not show that these rural micro distribution projects have the usual issues of grid connected metering, community mobilization, usage coordination, and diffused responsibilities. Metering is required to measure the usage of small amounts of power for lights and TVs. Their study also did not include the demand curves of the customers who do not have either the ability or willingness to pay the high costs of the mini-grid based power, which is also limited to 6-8 hours per day.

SPV-based mini-grid electrification in the Sunderbans Island has been examined by Nouni et al. (2006) and others (Shrank 2008; Chaurey and Kandapal 2010). This model has received mixed evaluations on both the successes and failures of its replication in other places. The mini-grid model has been criticized by Shrank (2008) as a top-down government subsidized plan with a heavy dose of subsidies and battery costs with no clear responsibility for ownership and maintenance. Users know that a much-publicized plan will continue to be subsidized by the government, leading to poor revenue collection. No competitive SPV market will develop when the government guarantees subsidized SPV in grid or mini-grid systems in a single, cooperative, or franchised system. Such systems would be similar to the grid-based systems in the USA and EU without the advantages of their high scale, competitive grid market, and demand side affluence.

They are dependent on subsidies, high technical and managerial skills, and a high level of community mobilization not seen in most parts of the country (Millar 2009; JABA case study, Chapter 4). Community mobilization has also been a perennial problem in India for biogas and biomass plants that generate electricity for community supply as shown by Reddy (1998) in Pura village, Karnataka and by Malhotra et al. (2000) in Dhanawas village, Haryana. A high level of management and coordination skill is required to manage the mini-grid projects, and often, villagers are not capable of managing a mini-grid without external help. The much publicized Pura biogas based power plant to supply rural electricity was infeasible due to non-payment for lower value added lighting services and was converted to provide more valuable rural water services where the biogas plant supplied power to pump water for storage in an overhead tank. With the value of water being more valuable than electricity, villagers presented a more cooperative attitude. It is also possible for village entrepreneurs to use biomass and biogas power for productive uses, such as for a village café as we plan to do in our case study, or for irrigation and drinking water, and rice de-husking projects. These are off grid productive uses managed by a single entrepreneur or jointly within a close-knit community or family.

The cost comparison of such mini-grid photovoltaic systems through a recent survey by Cust et al. (2007) with off-grid systems shows that mini-grids are about 10% more expensive. Chaurey and Kandapal (2010) also have shown that small 18-37W solar home systems are cheaper and more reliable than the SPV based micro-grid when the villages are widely spread and have less than 180-270 customers and are 1-4 kilometers from each other

The mini-grid is important for places where biomass, wind and hydro resources are available near a cluster of households with low access to shadow-free rooftops or backyards. However, the training in management and technology of such systems must precede any such energy projects. We will therefore turn to off-grid SPVs and will describe their merits and demerits and why we prefer this third approach to study the dominant market model. In my thesis, I will show how an emerging SPV fringe might address fossil-grid disruption and economic issues in rural India that might challenge the grid monopoly. This has not been examined in the literature since Lovin et al. (2002; 2005) published the book “Small Is Profitable” in the context of the USA. Reddy (1998; 1999) provided the conceptual framework, supporting off-grid SPVs in rural India to isolate urban areas from the negative commercial effects of the rural grid. The non-profit organization, Barefoot College in India, trains thousands of solar technicians for poor and rural economies of the world, showing the promise of solar electrification for them (Roy 2005; www.barefootcollege.org)).

The technical and externality costs of the fossil-grid are high, and there development is urban biased worldwide where the scale economies of production and consumption are achievable. We also saw that the renewable grid continues to remain urban biased. Though the emission and ecological externality costs can be removed the continuing dependence on the monopoly market and its imperfect regulators do not create any hope of market efficiency and economic delivery of electricity to the rural poor. I will show now how the costs, demands and competitive landscapes of the off-grid renewables in general and SPVs in particular are all in support of a subsidy free, development oriented and sustainable rural electricity market befitting India's rural resource endowments. This discussion will show that a monopoly, which perhaps was unavoidable in the last century's grid, is no longer indispensable in this century and can be replaced with competitive market for electricity in rural areas. The rural electricity market will be primarily based on SPVs and other off-grid technologies, where the urban grid will be left to market based competing suppliers from multiple grid suppliers, contrary to the argument by IEA, IEP, World Bank and others discussed before.

2.4 Off-grid Renewable Paradigm

Biomass and solar renewable energy are two resources abundantly available in Indian villages. Indeed, India might have comparative advantages in these two technologies as shown from the Global Energy Network Institute (Meisen 2006). Additional information on the availability of such technologies can be found on the MNRE website (MNES 2004 www.mnre.gov.in) and (Banerjee 2006; Kar and Dahl 2004). Though I will focus on the SPVs as the off-grid renewable, the abundance of Indian rural renewable energy is conspicuous for its biomass endowments. The off-grid SPVs are very attractive for the premium energy need for lighting and ICETs. The SPVs procured in small quantities are also affordable when biomass is cheap and available in abundance for the larger heating needs. Modern biogas, biomass and solar heat and cooking technologies are very basic, low cost, and widely available.. As heat is currently not derived from electricity in rural households, the demands for electricity will not include heat, and we could have deferred the biomass analysis for future study. I preferred to keep some biomass literature to show the completeness and competitiveness of the village energy markets. On the one hand, biomass acts as a substitute for the grid preventing the grid from achieving economies of scale. On the other hand, the same biomass complements the SPVs in rural areas by taking the heavy heating load burdens away from SPVs and meeting those household needs at lower costs. Thus, an SPV-biomass hybrid system costs less than a grid–biomass hybrid or grid-only system. I will therefore cover the biomass literature to show its competitiveness to the rural grid up-front cost in the literature review and theory section and then drop it for the detailed data analysis in the dominant firm model.

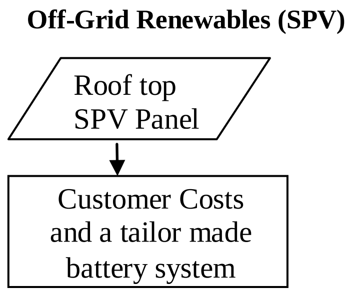

Figure 2-10 A simplified schematic diagram of the off-grid SPV system

Off-grid energy technologies are much simpler, more isolated, and more decentralized. No interconnection with other systems reduces issues of cost sharing and externalities. The geographic spread being confined to the customer's premises, they will create less environmental damage and have fewer interruptions compared to the rural grid. The need for batteries is very customer specific, but essential for SPV off-grid technology as sunshine is intermittent during the day time and unavailable at night. However, such battery support is also required for grid connected systems because the grid itself is so unreliable. Fortunately, for poor households, SPV battery support is minimal and meets both the needs of electric reliability and portability that I will discuss next.

2.4.1 Rurality ensures availability of low cost off-grid renewables

a. Biogas/Biomass/Solar Heat for cooking take the heavy weight of rural energy reducing the residual electricity demand to a miniscule amount

Rural biomass can provide 80% of rural domestic energy. Reddy (1998), MNES (2004), Ravindranath (2005), and Pohekar et al. (2005) suggest that many components of rural energy demand such as domestic cooking, heating, and rural productive needs can be met from local biogas and biomass thermal resources. The costs of these technologies are lower than grid electricity costs, and there are significant opportunities to increase local production and jobs through the introduction of these technologies through both a stand-alone off grid and a mini-grid environment (Miler 2009; IEA 2008; TERI 2003b). The demand for cooking varies around 0.5 kWh per capita per day of effective energy in the pot and comprises 70-80% of rural energy needs (Dutta et al. 1997). Biomass cooking can easily be done with a solar cooker or a biogas stove at a price of less than 2 c/kWh for 30-40% of rural households. These have significantly lower costs than the lowest average grid cost (Locayo 2006). Modern cooking devices like solar cookers and biomass are widely available, aggressively promoted and are offered with micro finance, as suggested by Bhattacharyya (2006). Biomass or solar heat energy can have a horizontal supply curve, if the small-scale suppliers participate in the local rural market. The remaining energy needs for lighting, fans, and TVs can only be provided by electricity. With appropriate conservation, small village level entrepreneurs can provide such electricity, which is safe, reliable, and affordable, through solar PV and battery based systems, depending on the value and paying capacity of the consumers.

As Box 2-1 shows, the highest energy consuming sectors like heating, cooling, and cooking loads can be replaced first by conservation and then by modern biogas, solar, geothermal, and biomass, which are plentiful and cheap in a rural Indian home's backyard. A very high cost SPV supply can be used only for a very low quantity of energy demand derived from high efficiency lighting, fans, refrigeration, laptops, LCD TVs and other ICET appliances for improvement of standard of living, health, information, education, and entertainment goods.The drastic reduction in energy requirement makes the traditional argument that electricity cannot be economically stored in large quantities irrelevant. This helps us to zero-in on the important modern technology of off-grid SPVs as the focus of this study. I will argue that the current electricity demand of rural areas can be effectively supplied from the SPVs at a lower cost than the grid. I will provide a few reasons below why the battery costs are not relevant for my cost calculations.

1. The rural poor do not need to store a large quantity of electricity for home lighting and ICET use. They will most likely require one portable electric lantern and one cell phone operated by battery even if the grid is supplied. These devices will already have a built-in battery for portability whether they are charged from the grid or SPVs.
2. The relatively rich households already use stationary battery-inverter systems for essential back-up power for running lights, fans, and TVs. Thus, batteries are not new to them. The urban rich might use smaller systems for a few hours of power outage a day, but the rural rich will have to keep larger batteries for days of power outages in the villages.
3. The batteries are generally purchased from the competitive open market without any subsidies. Thus, batteries costs also do not appear in the subsidy calculation.

4. The costs of rechargeable batteries are falling due to innovations in the electric vehicle and portable electricity markets. Thus, the cost of battery backup will not be significant for the rich people compared to their total power consumption.

In order to not complicate the calculations of the costs, demand, and subsidies, I neglect the battery costs in this study.

Box 2-1 The method of implementing off-grid renewables in Indian villages

The solution I will provide here is not to provide free electricity irrespective of its use, but rather to make arrangements so that anyone, irrespective of his/her economic condition, has the option to use modern solar electricity to improve his/her livelihood. I start with the typical rural USA average consumption of 700 kWh/month (kWh/m) for a 1500 square foot (sq. ft.) house. The conservation, efficiency, and day-time lifestyle pattern in rural India can reduce this energy consumption as shown below. The goal is to reduce the need for a battery, which is considered a deal killer. The weaknesses of storage batteries are their low life and high cost that can potentially double the off-grid SPV costs.

1. Conservation: 80% less electricity (20% of USA) = 140 kWh/m average 200-400 sq. ft. house

a. Use less: Village culture, small land holdings, and small dwellings are appropriate for small SPV systems, hand pumps for drinking and irrigation water. Local food production from backyard farms will also require less cold storage and commercial energy.

b. Cooking and heating: Maximize the use of rural but cleaner biomass and biogas, which is low cost and high value, will greatly reduce the pressure from SPVs for supplying heating energy.

2. Efficiency: 20%-50% of Step 1 (28-70kWh/m)

a. Home: Passive solar, thermally optimize building, mud brick, optimal tree plantation and shading practices in yet to be designed homes for the poor will reduce the cooling loads.

b. Lighting: CFL for space, LED for directional, street, and parks; portable lanterns

c. Motive power: High efficiency DC Fans, DC Pumps, DC Huskers

d. Water supply: Low water faucet, toilet, and drip irrigation; water reused from biogas for home use in kitchen and garden

3. Defer to daytime production and consumption: 50% of Step 2 (14-35 kWh/m to avoid battery storage)

a. Water supply for agriculture, home drinking water

b. Food production, cold storage. Ice making maximized during day time. Most of the cooling fan loads can be supplied during the day without a battery.

4. Non-electric storage until battery technology improves 50% of Step 3 (7-18kWh/m)

a. Water in overhead tanks for 3 days

b. Food, fodder, fuel wood can be processed in the daytime and stored as is being done today

c. Fruits and vegetables straight from the garden, milk and yogurt from local dairy farms or stored in an earthen pot each day. There is neither need, nor is it healthy to store for days

5. For remaining 50% battery storage essential for ICET, evening lighting, and comfort (7-18kWh/m)

a. TV/Computer

b. Fan in summer months

c. Maximize the existing battery in laptop, DVD player, ICET uses

b. Off-grid electricity is simple and lacks interconnected reliability issues with portable/stationary battery support:

An Indian village will need about 28-70 kWh solar electricity per home, out of which 7-18 kWh/month is for battery storage as shown in Box above. An SPV-battery system, when and where the sun is unavailable, can be used for a reliable and portable power supply, often most essential for rural uses. Although I discuss the available and emerging battery technologies that will help develop the rural electricity infrastructure, I argue that the battery costs are not very relevant for competitive analysis with rural grid. Since battery storage is already required by the grid-electrified homes to protect costly appliances from the vagaries of low voltage and lack of a reliable rural grid, the cost of the battery system does not disadvantage the SPVs in the comparative cost calculation. The two most popular battery technologies normally used for solar and cordless applications are now ready for wireless/off-grid rural electrifications:

1. Pb-Acid/Ni-Cd/NiMH (Traditionally these batteries are used in small, short life, portable devices or for stationary Uninterrupted Power Supply (UPS) emergency backup; they have high cost and a short lifecycle).
2. Lithium batteries for portable devices (power tools/vacuums/sweepers/mowers/laptops/cell phones). The relative cost, possible number of charging cycles, and other technical and environmental characteristics of these are shown in Table 2-7.

The most energy hungry item is a laptop, which requires a large solar panel and/or more spare battery capacity. Most of the other devices can be charged from on-board solar panels like those manufactured by Konarka/Schott Solar/as plastic solar panels in backpacks and vanity bags for direct or even indirect sunlight or artificial light. As the power consumption is small, charging from a diffused indoor light over longer periods of non-use can be sufficient for a few minutes of use.

For appliances and many personal devices that are used less frequently, there are fewer charge-discharge cycles, which in turn results in longer battery life and lower cost. New lithium phosphate batteries with 2000 cycles have a cost below sealed lead acid batteries, at a much lower weight and volume. As can be seen from Table 2-6, Lithium Iron Phosphate ($LiFePO_4$, LFP) is a new development in a Li-Ion rechargeable battery for high power applications, such as EV cars, power tools, and hobby projects. LFP cells provide high discharging current and are non-explosive as their energy density is somewhat lower than normal Li-Ion cell (Li-Co) but much higher than other cells. Their working temperature is also a better fit for the warmer Indian climate than for other batteries; however, they might not be suitable for a colder sub-zero climate. A new USA company, 123Systems, is pioneering this technology and has been awarded DOE grants and commercial orders for supplying a lower cost battery for electric vehicles. Their 5 kWh battery pack, which is already on the market, can convert a Prius to a plug in hybrid electric vehicle (PHEV). In this gasoline-electric hybrid the battery and gasoline engine work together to provide 100 miles per gallon up to first 40 miles until battery is discharged. As long as the daily commute is less than 40 miles, average consumption is 1/2 gallon/day of gasoline and 5kWh/day of electricity. There has been much interest in India and world for small pure electric vehicles that will be useful in an Indian village community where one vehicle can be shared and the daily commute will involve short distances and slow speeds due to high population density and poor road conditions. This type of battery technology, if advanced, will provide a great advancement in off-grid rural SPV technology with lower costs, greater safety, greater thermal stability, a longer cycle life, and a higher energy density as shown in Table 2-7.

Table 2-7 Comparison of commercially available battery technologies competing in the off-grid market

Chemistry	Voltage	Energy Density Wh/kg	Working Temp. °C	Cycle Life	Safety of operation	Environmental Impact	Relative Cost based on cycle life x Wh
$LiFePO_4$	3.2V	>120	-0 to +60	>2000	Safe	Good with no heavy metal, fire safety, can be recycled	0.15-0.25 lower than SLA
Sealed Lead Acid (SLA)	2.0V	>35	-20 to +40	>200	Safe	Not good due to lead but flooded batteries can be recycled	1
NiCd	1.2V	>40	-20 to +50	>1000	Safe	Bad due to cadmium	0.7
NiMH	1.2V	>80	-20 to +50	>500	Safe	Good except for heavy metal	1.2-1.4
$LiMn_xNi_yCo_zO_2$	3.7V	>160	-20 to +40	>500	Better than LiCo	OK except for heavy metals	1.5-2.0
$LiCoO_2$	3.7V	>200	-20 to +60	> 500	Unsafe without control	OK some fire safety and unstable chemistry issue	1.5-2.0

Source: www.batteryspace.com.

Even if I discussed here battery technologies as an important driver of and complement to SPVs in the off-grid homes, communities, and rural businesses needing reliable power, I do not compute the costs of battery backup for rural household, community and business levels. I will show that the communities and business in rural areas like in poor households can use portable solar lanterns, stationary solar home and entertainment systems, streetlights, and possibly electric vehicles. All these will all have to be designed with batteries to make them reliable and usable. Batteries are common for both the rural grid as an unreliable energy carrier and off-grid SPVs as intermittent energy resources for poor community uses. I proposed that if the low demands today of poor households, communities, and production increase significantly in future, a separate study should be taken up to analyze battery costs in greater detail for the appropriateness of rural dispatchable biomass power to complement SPV's intermittency, as considered next.

Biomass power complements SPVs and can substitute larger batteries for rural production: Biomass power for community production, transportation, and battery charging has been demonstrated in the Indian context. (TERI 2003c, Indian Institute of Science, MNRE, Ankur Technology; India). The Energy Research Center (TERI), and Indian Institute of Science, Bangalore provide some of the commercial renewable biomass/biogas cook stove suppliers in India. If the SPV price is not attractive enough in the next few years for powering the growing needs of large motors or cooling systems, biomass-based electricity can also be generated in most villages at a lower cost than the grid as shown by the Indian biomass projects developed by DESI power. This off-grid model can use SPV-biomass hybrid systems for productive uses, including home businesses, cottage industries, small roadside shops, and tailoring and carpentry in all parts of rural India. The SPV powered agricultural pumping systems in the Punjab have been successfully tried (Redulvoic 2004). The Fishbein (2003) survey has shown a significant use of renewable energy projects for productive application in many countries including India, the Philippines, and other countries. April et al, (2000) have shown how schools can be electrified with SPVs. Mukhopadhya et al. (1993) and Ramos (2009) have shown how SPV water pumps are very cost effective in rural water pumping applications when the load is constant or matches with the solar irradiation, which is most often the case. Mostly, drought and high solar conditions increase the water demand. Winter has a lower water need. Ramos designed a water pump with a 195W solar panel to deliver one cubic meter of water from a 100 feet deep well, at the cost of about one Eurocent per liter. Night time use of water is possible by storing in overhead tanks and the cold storage is possible with ice storage inexpensively without battery support. Biomass power has been shown by Ankur (2009) and Kishore et al. (2009) to cost 7-15 c/kWh much lower than the grid power in rural India.

However, these larger electricity systems are not immediately required for the rural poor. They require careful training and skill building for many years before adopting such larger systems for productive uses. These more complex technologies will not be considered in this thesis as immediately relevant for the rural poor.

c. Rurality implies availability of land and SPV resources close to where the energy is used

The opportunities that rurality, poverty, and lack of electricity present to the future of the SPV energy systems will be discussed in this section followed by the competitive market place for off-grid energy systems that require fewer or no subsidies.

1. SPV systems for lighting homes, schools, streets, and shops have been popularized by practical implementations through government, non-profit, and private agencies (MNRE, SELCO, BP Solar, Haryana; India). SPV powered ICET for community health, education and entertainment have been recently getting the attention of international development agencies and national governments (UNDP, World Bank, Cuba, Chile, Tunisia, and China). Though this effort started on an experimental basis in the late 1980s and early 1990s, the success of these systems was limited by the limited availability of funding and the high cost and poor reliability of the emerging technologies. Much work has since been done on SPV material technology to improve efficiencies and the productive life periods of the SPV systems: solar PV panels, charging and load control electronics, and battery systems. The main technologies along with their efficiencies are as follows:
   a. Crystalline SPV Panels are more efficient (12-20%) and are useful where space limitations exist. They are more widely available but their costs are relatively high. They are categorized as:
      i. Mono/poly crystalline
      ii. Multi junction
      iii. Concentric/back contact
   b. Amorphous SPV Panels with lower efficiency (6-15%) are lower cost per kW and are more useful for rural areas due to less land restrictions. But their availability in rural India is limited and new suppliers are now targeting only the SPV-grid market and government subsidies. Over time, the off-grid market is likely to develop. These panels have the advantages of better temperature and shade resistance and more output for the same nominal watt panel. The costs of SPV cells and panels comprising arrays of cells are measured in terms of dollars per peak watt ($/Wp) based on the standard solar irradiance of 1000W/square meter at 25 degrees Celsius. The technologies that are already commercial are based on the following chemistry:
      i. Silicon (Indian firms 1-2 $/Wp for panel; 4 $/Wp system)
      ii. Cadmium Telluride Cd Te (First Solar < 1 $/Wp)
      iii. CGIS (Nanosolar Printing technology < 1 $/Wp)
      iv. Flexible Organic Dye (TiO2 cold sintered dye sensitized, broad spectrum < 1 $/Wp)
2. PV-Inverter-MPPT (Maximum Power Point Tracker) systems are used for drinking/irrigation pumping, daytime production, ice-making, and product storage. MPPT are used to maximize output from the low radiation conditions during dawn and dusk

when the temperature is low and the voltages are high. By running the SPVs in optimal Voltage – Current (V-I) condition, MPPTs can increase power output by 10-30%. The solar water pumps for farming were disseminated in the Punjab, and their application in rural USA is becoming popular. Our village case study in India, described in Chapter 4, also indicates that such SPV powered water pumps are important integrators of sustainable energy, water, and lifestyle needs along with their potential applications in small-scale productive activities.

3. Most of the costs of SPV system in developed nations are the engineering and installation costs due to high costs of labor and the mandatory certification of the relatively large grid connected system that are being promoted to ensure safety of the equipment, utility personnel, and the public. In the off-grid small SPV systems that are required for the rural poor no such costs are involved. Unemployed semi-skilled technicians can be readily deployed to reduce the costs of solar systems. Most of the operation and maintenance can be left to the users themselves. Thus, the total installed system costs could be less than $4-5/Wp once a full deployment is laid out. Just as the cell phone industry in India captured the rural market through low cost supply from dysfunctional or unavailable landlines, it is now time for the off-grid SPVs to take over the market from the dysfunctional rural grid.

d. SPV technologies despite their need for battery are simple, modular, safe, popular, and risk-free

The small-scale SPV technology is popular among the small and large civil society organizations. They have been found to be very much interested to

- disseminate SPV based small systems to the poor, teach rural women how to assemble, care for and maximize the output by periodic maintenance and alignment of solar panels (Barefoot College in India)
- diffuse the high transaction costs by involving grass root volunteers in rural projects reducing the costs of operation and training
- mobilize funds through the aggregation of small donations or investments
- use the power of the internet to increase the utility and effectiveness of small aid to finance rural projects, impart training in operation and maintenance, and use e-commerce to sell locally made solar products.

The “Light Up the World (LUTW)” foundation showed from early 1998 how it is possible to use SPV panels with as low as 3W of capacity to power bright White Light Emitting Diodes (WLED) in poor communities in the hills of Nepal. Two WLED systems from LTUW will cost less than $60; an LED powered study and work lighting product is available for retail in India at $40, with free home delivery from BPL India; Compact Florescent Lamps (CFL), called "Solar Lanterns" in India, now cost less than $80 (BP-Solar, India). They are also rapidly expanding to off-grid LED devices for rural and urban applications. The larger and next most popular 40W solar panel can power CFLs, a TV, and a fan for 3 hours a day, with a rechargeable battery at $400 (BP, Solar India). About a million such systems had already been installed in India by 2008 (MNRE 2009). Chaurey and Kandapal (2009) have shown that a solar CFL lantern can be rented to the rural poor at $4 per month and a LED lantern at $2 per month. Banerjee (2008) compared CFLs with LEDs when the luminous efficiency of the LED was 47 lumens/W and the equivalent efficacy of the CFL was 63 lumens/W. His study found CFL superior to LED based on the cost of lumen output. Now high power LEDs are available at lower costs and higher efficiencies. LEDs, with more than 100 lumens/W, are now available though at a higher price (CREE 2008). Thus, the cost of LEDs in terms of effective lumens/W could be more competitive when directional lighting is required for example for display, projections, study and rural street lightings. Further, LED lamps have longer lives, are non-fragile tolerating some shock, and are cool to touch, fire safe, and mercury free. These directional, cool, and safe lights can be used inside mosquito nets to provide a comfortable place for children to study or parents to work without disturbing the sleep of others in the single roomed huts of poor households. No other CFL or grid lights can meet such needs in the tropical mosquito ridden climate of India.

In order to rigorously prove that economic costs of off-grid SPVs are lower than the economic costs of the rural grid, I will use an economic model of costs as shown in Figure 2-10. Since SPV devices are long lasting capital investments, there is a need to convert these capital costs to annual/monthly fixed costs and then determine the average energy costs similar to what is done for the rural grid. The only difference with the rural grid is that there will be no variable energy costs as sunlight is free. I will use the same financial parameters as used for the grid with a 14% cost of capital with no taxes and a 25 year asset life.

The Indian government has set a minimum threshold electricity consumption of 30 kWh/month per household. I will use this quantity as the administratively fixed vertical demand Qr* to compute the average cost of grid supply from the LACr function. But off-grid SPVs have the additional advantages of a modular nature and can be delivered in very small sizes as represented by the small U-shaped average supply curves in the figure. Whether at a low quantity demand of Qs kWh per month driven by poverty or high efficiency or at a high quantity demand Qh driven by high income, the cost of SPVs is constant at Ps as shown in Figure 2-7. It is clear from the fixed demand schedules that there is a threshold consumption Qo below which SPVs are cheaper than the rural grid (Ps<Pr) and above which rural grid is cheaper (Ph<Ps). My objective in the first question (Q1) is to determine these SPVs and grid cost curves and threshold consumptions in Chapter 5. No such side-by-side comparison of the grid verses renewables is available in the literature that also considers their demand and supply curves together.

Another point worth noting is that even though Ph is less than Ps, the monthly cost Ph*Qh will be much higher than the Pr*Qr or Ps*Qs that can be affordable by the poor. Such affordability and willingness to pay is derived in the demand curves of the poor households. I will now consider literature on how the low demand of the rural poor can be met effectively through efficient devices using renewable energy that fossil-grid has failed to do. This will also be analyzed in Q1.

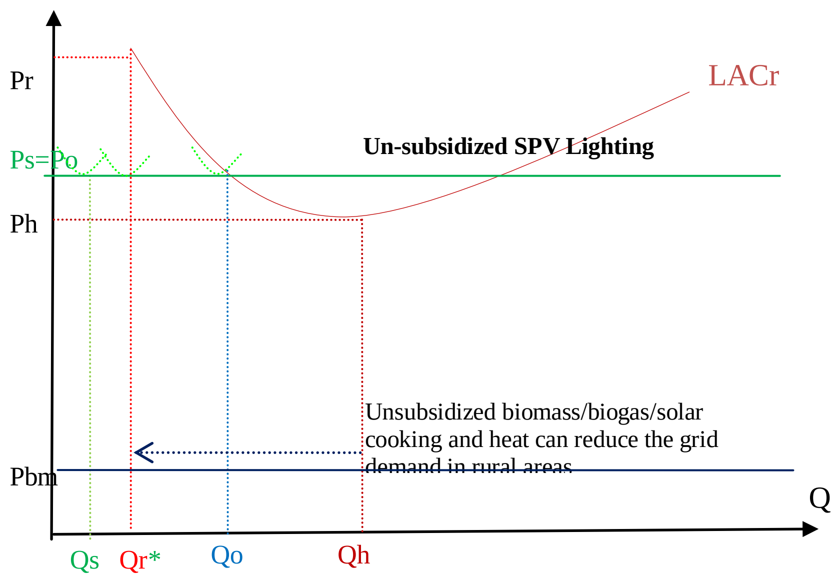

Figure 2-11 Which is cheaper: Rural grid or off-grid SPVs? Author's depiction of a cost model to answer Q1.

2.4.2 Rural Indian poverty and conservation culture lowers electricity demand, but shows willingness and ability to pay for quality electricity.

In section 2-2-2, I have shown that the poor income base of rural India does not show promise for the rural grid. Here I will show that the same poor income is not a great handicap for solar technologies as they are designed to meet the specific rural needs of reliable evening light with features of portability, multi-functionality such as battery charging for radio, TV, and cell phones. I will explain below how small the demand for electricity by the Indian poor really is. The large-scale grid is inappropriate to supply such minuscule energy especially when considering that the poor quality of the service in grid electrified villages and the lack of complementary factor inputs have not transitioned the poor to be more developed economically or socially. I will use the demand model from the village case study to show such interactions in Q2.

A possible role of off-grid renewables in powering the modern efficient devices for rural health, education, lifestyle and production uses are shown in Table 2-8 that has not been solved effectively through the rural grid. The electricity is a derived demand from these social and economic end-uses. However, if these end users are not modern and people are still depending on primitive lifestyle and production methods, electricity will not be demanded, as we will see in our case study. On the contrary, if the villagers were provided reasonable opportunities to use all the inputs for meeting these end uses their smaller needs for lighting, fan, and communications can be met easily through small scale SPV systems. The SPV and efficient devices fit into these demand requirements easily because they allow electricity to be packaged to the specific needs of the poor in a phased manner as they demand more and more in small discrete intervals. The large -scale grid supply cannot fit this model as the supply has to be large, which means the grid will remain unutilized for long hours in these poor economies making the payback period long. I will provide empirical evidence of how low demand for electricity can be through the modern efficient ICET appliances to provide the rural services shown in Table 2-8.

When income is high, theoretically, there is no problem of getting a subsidy-free supply of grid electricity. The demand curves in Figure 2-12 shows the demands for SPV electricity, even when income is low and demand is D_L, can be subsidy free. While D_L is completely cut off from the grid market and stuck with kerosene, they can be easily enticed to use SPV lighting. As argued by Cheroensky (2002) and as I will develop in the theory section in more detail, D_L illustrates a low but non-zero quantity demand at a very high price satisfying basic needs for lighting. With income as low as this, the grid price Pr equilibrium can be achieved in the absence of any other substitutes but it will be extremely high. The grid costs are so high that even polluting and tedious kerosene fuel appears cheaper; moreover, many people prefer kerosene lights for the added advantage of portability and versatility of use in homes, roads, and gardens that the grid cannot provide at lower costs. But the SPV lanterns are safe, portable, weatherproof and brighter, and the solar battery in it can provide multiple services from playing the radio to charging a cell phone. [10]

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[10] Even poor homes now buy a cell phone because of the high value it provides by keeping people in touch, avoiding the need of long travel; it is portable, sold in a competitive market, and the price is very affordable. Such a model

Table 2-8 Potential of off-grid SPVs where the grid has failed

Output	Derived Energy Demand from Final Product Demand	Efficient Appliance Required	Local Energy Resources
Health Nothing significant done by grid as polluting kerosene/biomass are still being used for lighting and cooking	Water pumping,	DC Pumps	SPV
	Health center, electrification and video conferencing	LED, CFL, medical devices, laptops, amenities like fans and TVs	
	Processing and storage of food	Hybrid electric and bio-gas freezers	Biogas/SPV
Education Nothing done by grid today for rural poor. It is possible to teach and impart skills with modern gadgets and distance courses through ICET and solid state lighting and projectors	Lighting,	LED/CFL	SPV
	TV/DVDs/laptops	LCD TVs	
	Comfort	Fans	
	Projector power for modern interactive education	Efficient mobile LED projector commercially available	
	Transport	Walking, biking, solar powered rickshaw	SPV//Bicycle
Lifestyle/Quality of life Today only 10% of affluent villagers use subsidized electricity for lighting, fans, and drinking/irrigation pumps with provision of back up battery/diesel power very inefficiently. These can be made very efficient through off-grid systems	Cooking	Smokeless cook stove	Biogas/Biomass
	Lighting	LEDs//CFLs	SPV
	Electric sweeper/tools/blenders, /small electric appliances/	Small sweepers, blenders, microwaves, mini compressors	
	Connectivity, entertainment, arts, and cultural events	Cell phones/Wireless router/TV/DVDs/Photography /eBooks	
	Transport	Battery Van/assisted	
Production Nothing done by the grid yet except for basic de-husking and ice factory. training center and low power devices can be used for farm and manufacturing	Food processing	Electric Powered bi/tricycle	Biomass/Biogas
	Brick making	Hand operated	Manual but more efficient devices
	Software	Laptops/Servers	SPV
	Irrigation pumps/ tractors/harvesters/ electric vehicles and solar operated small vehicles	SPV for water pumping and more research on bio fuel and electric technology for future (solechaw)	SPV/Biomass/ biodiesels as alternate fuel are emerging

Source: Compiled from the World Bank ESMAP (2002; 2003; 2004), Barnes et al. (2002), and IEA (2002) and adopted for a village in India

SPV lighting can compete with kerosene better as shown in the figure, unless the kerosene price is more heavily subsidized than as shown. In India, the rural kerosene price remains at Rs 10-12 /liter irrespective of the market price of the fuel that can go from Rs 40-60/liter. There will also be no problem in achieving equilibrium of solar PV lighting because for lower income customers, there is now more efficient and lower cost LED lights powered from 2-10Wp solar panels available in the market.

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should work for SPV to compete in the rural market. Although the government is also owned the rural land line telephone companies, they were easier to bypass since they were not as heavily subsidized as the rural grid.

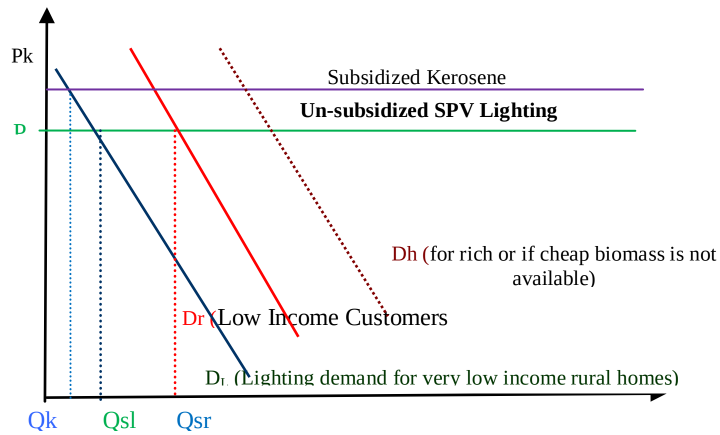

Figure 2-12 No need for off-grid SPV subsidies irrespective of income high or low, market clears all the time.

2.4.3 Evidence of off-grid SPV's efficiency and competitiveness

Now let us discuss the competitiveness of these off-grid SPVs. Table 2-9 shows the costs and subsidies already provided by the government for these technologies in various countries. The comparison with the grid will show that not only is the absolute level of cost per customer low, the percentage of subsidy is much lower than the percentage of subsidies for the grid (12-60% in Table 2-9 against the 90% grid subsidies shown in Table 2-3 for poor Asian communities). This shows the increasing competitiveness of SPVs. Furthermore, the subsidies have probably been necessary only because grid electricity is also subsidized not because income is too low to clear the market. I will prove in this study that SPV market clears at any income. The competitive market in SPVs can be immediately possible if instead of direct subsidies, an income transfer is made to the poor to purchase these devices, or the capital market can be used to deliver the energy services as shown by Miller (2009). There is absolutely no need for government ownership and regulation of the industry as in the grid.

Table 2-9 Off-grid subsidies for SPVs in some developing countries

Item description	**Tunisia**	**Chile**	**China**	**Philippines**	**India**	**Bangladesh**
Solar PV System Size of-grid	100Wp	50-100Wp	15-50Wp	20-100Wp	10-40Wp	20-70Wp
Upfront Cost in $/Customers	1900	1000	100-300	200-600	70-320	70-400
Subsidies % of Cost	**100%**	**90%**	**15-22%**	**20-60%**	**12%**	**12%**

Source: World Bank 2008; 2009.

If off-grid SPV systems are too costly for the very poor villagers, who need to pay for food and clean water rather than for solar light, they can still use reliable street lights or community centers for free lighting, health, education, and entertainment during the night. In addition the surplus solar energy stored in a solar lantern can be shared, rented, and sold for others to use to earn some money. Renting a highly valuable lantern and putting it into other productive uses due its portability and illuminating power, of course, requires business skills but an owner or renter can also make use of barter trading prevalent in some communities.

The alternative development proposal in this thesis will address the demand and supply issues of the current fossil-grid head on by showing how to reduce costs, eliminate regulation of the top-down electric grid system, the elite capture and power theft, and minimize direct subsidies without seeking cross-subsidies. These goals will be achieved by renewable energy, which has little or no pollution or global warming related costs. It will be achieved better, by non-grid intervention through a bottom-up approach so that the rural grid failures that we discussed will not be any handicap.

The indirect economic benefits such as health, increased study hours, and a better quality of life, have been imputed to justify these projects compared to the benefits of kerosene lighting (Barnes 2002; MDG, Modi 2005). However, the ability and willingness to pay is a necessary condition for providing commercial energy services.

To my knowledge, no past study has attempted to quantify this threshold income representing the ability to pay and which is absolutely necessary to make the gird and SPVs subsidy free. This threshold income will be analyzed in this thesis to bring into focus how poverty is the driver of the low electricity access and how the off-grid SPV alternative is better. This demand curve will be estimated from the village household data and cost of the grid will be determined from the recent government RGGVY and empirical data from a representative village, as noted before, to show this equilibrium. The study will also show how the demand for SPVs can grow in phase with income growth, solar PV cost reduction and increasingly familiarity leading to an efficient, competitive market supporting further innovation by numerous market players. Q4 will be a dominant firm market analysis that will be discussed in the next chapter.

Similarly the quality, reliability, and portability of electricity influence the willingness to pay. Such willingness along with the ability to pay has a profound policy impact on grid verses solar PV investment in poor villages. To my knowledge, these issues have not been examined by the other studies but will be examined in this thesis through the case study in chapter 4.

2.4.4 Off-grid renewables promote market, competition, and efficiency now and in the future

a. No Monopoly and economic externalities: Moral hazard and adverse selection occur when supplies are local and competition is fierce from biomass and biogas heat.

Lacking the need for monopoly and cost-plus pricing regulation, the decentralized SPV market will be void of moral hazards rampant in the grid industry. The user will often own the power-generating devices, reducing the moral hazards for the proper upkeep of these devices. Adverse selection is also minimized, as there will be no ad hoc administrative pricing asymmetry that will generate a gaming opportunity. Users and suppliers, being either the same or close to one another, break the informational, organizational and distance barriers that create externality, information asymmetry and the nontechnical costs of the adverse selection of grid technology, which we discussed earlier. As there is no role for meters, inspectors, and auditors in such simpler off-grid systems, the chances of corruption are lower. Unless government planners and executive agencies mismanage the implementation of an otherwise competitive SPV market or drive these grand projects as a political business, multiple buyers will chose varieties of products from multiple suppliers. The entry of private players is also very easy in the SPV field compared to the decades of worldwide privatization in the grid industry, which has been an almost total failure in the Indian power industry. By avoiding the needs for high subsidies and a rural urban joint business model, regulation or subsidy administration by government agencies is also avoided.

b. No energy scarcity/No elite capture/No emissions

SPV is a technology product produced from abundant raw materials: silicon as the semiconductor with aluminum and other metal frames. As with electronic devices, the costs fall with time, there is strong evidence of the price of SPVs falling over last decades by more than 20% for each doubling of production. However, the fossil grid supply costs are increasing and unstable to reflect the costs of scarcity, price volatility and risk of non-renewable mineral based products, government involvement, and a long transportation network. None of these problems is applicable for SPV rural off-grid.

SPVs have many positive environmental attributes such as no emissions, no need for water to generate electricity, no natural resource exploitation, no large dam, and no noise. All conventional electricity generation technologies use large amounts of water in the power production process, and block, divert, or contaminate the water resources making it a scarce commodity. The Indian government's projection (CEA 2006;2006a;2006b) of conventional fossil-nuclear-hydro based power generation doubling in each decade will only exacerbate the water scarcity in each decade. Fortunately, SPVs and renewable energy in rural areas can reduce water scarcity pressure; SPVs use a negligible amount of water in the energy generation process. An off-grid SPV system can help extract water from the available underground and surface sources exactly at the time when it is needed most without costly battery backup systems. If it is necessary to water at night to reduce evaporative loses, or if water is needed during the night, it can be stored in inexpensive overhead storage tanks and effectively delivered through drip systems during the day or night. The water-friendly nature of solar electricity has enormous significance for heavily populated areas as well as semi-arid areas with water scarcity.

c. Positive externalities: The faster learning curve effect of SPVs

The learning curve of SPVs/Biomass/Biogas is generally used to explain how exponential cost reduction will be expected in high cost but newly emerging technologies. SPVs, energy efficient appliances, and devices like LEDs, electronics, and ICET systems all show such learning effects where the learning coefficient measures a 20-30% cost reduction for each doubling of the output. Figure 2-12 demonstrates the learning curve effects on SPVs in the European market. Grid parity is where the increasing cost of the grid (red lines) and the decreasing cost of the SPVs (green lines) meet. This grid parity is likely to happen by 2020 for the utility retail peak power at 0.20 euro /kWh in Europe even in places with low insolation of 900 hours of full sun per year. Similar curves are also observed in USA and worldwide market not only for SPVs but also for inverters, efficient LED lighting, and ICET devices and gadgets. These technology led cost reductions are in direct contrast with the scarcity and externalities costs of the fossil fuel that will eventually increase as low cost resources are exhausted. This will lead to growing competitiveness of solar photovoltaic through technological and market innovations. This raises the fourth research question (Q4), will the rural grid in India become competitive with SPVs by 2020 or completely loose dominance due to such learning curve effects. The learning curves of the SPVs will be used to answer this question.

The learning curve is dependent predominantly on global demand and encourages investment in SPV energy and supplementary technologies like batteries, electronics, and solid-state devices, which are still evolving. They have a great potential to reduce costs and increase supply. At the village level, the micro financing revolution as seen today in South Asia can accelerate SPV diffusion faster. The increasing use of SPVs by the villagers themselves will reduce the marketing, operation and maintenance costs through learning by using.

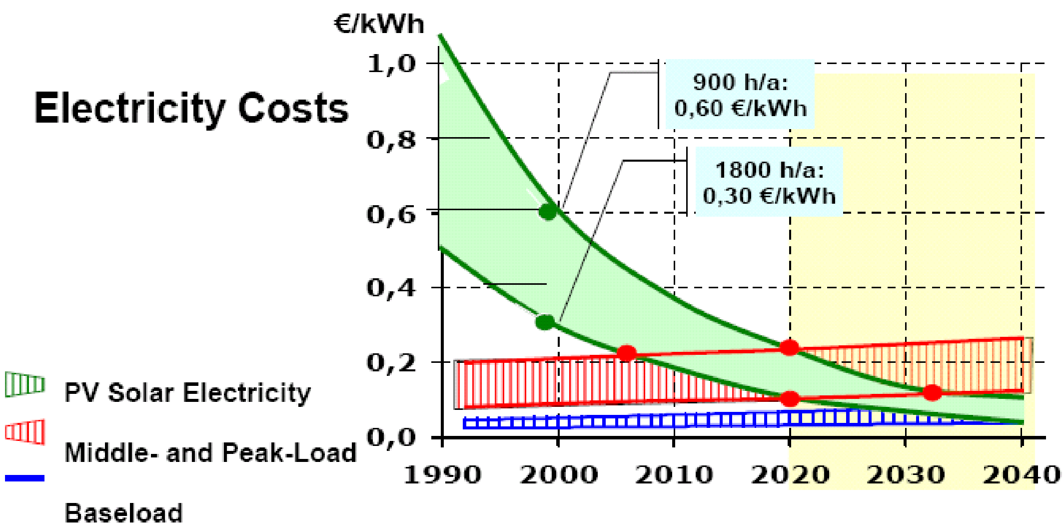

Figure 2-13 Grid parity of solar photovoltaic in lower latitude countries with the high solar radiation

Source: RWE Energie AG and RWE Schott Solar GMBH, comma stands for decimal in Europe. The full sun hours per annum are represented as h/a

The off-grid systems are different from the large scale, mini-grid, and village electrification programs undertaken by the Government of India in villages on remote islands. Non-government organizations and private market entrepreneurs in both rural and urban areas operate off-grid SPV businesses to fill-in for the portability and reliability shortcomings of the grid network. SELCO, India has a thriving business, selling portable SPV lanterns, head-lights to free up the hands, and home lighting systems to street vendors, houses, and urban residences near Bangalore where the power supply has been very erratic. A study by the World Bank (Miers 2006) in the Philippines shows that off-grid solar systems have at least as beneficial an impact as the rural grid with economic returns on the investment as high as 100%, considering all the socio-economic benefits. A similar study in India, Sri Lanka, Bangladesh, and Africa has shown promise for newly emerging off-grid technologies for rural applications (World Bank GEF 2004).

A few words of caution on off-grid subsidies: It has been argued that when the governments provide high subsidies for the grid, the off-grid market cannot emerge (Saghir 2008). Miller (2009) and NCI/Soluz (2006) show a high level of non-sustainable, one-time subsidies for off grid SPV products in India and Brazil, respectively. One time subsidies for off-grid SPVs without eliminating the much higher and perpetual subsidies to the inefficient grid only create transitional markets without long term investments in the off-grid supply channel. The investors, instead of being customer focused to drive SPV demand in a long-term market, try to maximize the short-term government subsidies for their bottom-line. These transitory high subsidies have effectively thwarted the emergence of a thriving market for SPV products in India and South America, as the lack of adequate financial resources prevent the huge required subsidies for both the electric grid and SPVs. Such subsidy driven markets are often taken over by government agencies supplying the solar products inhibiting the competitive private sector. Redulovic (2005) explains how the predatory pricing for SPV water pumps by the state's public sector manufacturer of electrical plants, Bharat Heavy Electrical Limited (BHEL), thwarted the entry of an emerging private sector producer of SPV water pumps. However, BHEL ultimately did not provide the after sales support for the SPV pumps, ensuring that the technology would fail. A recent book by Millar (2009) "Selling Solar" addresses such lopsided and ineffective support for solar energy.

A counter example is the Indian state Karnataka where the government did not provide huge subsidies to either grid or off-grid devices. This helped SELCO to enter the rural and even the urban markets through innovative products and financing arrangements that added value for consumers and created a thriving long-term market for small scale, portable solar devices in rural and urban areas.

2.5 Summary of Literature Review

In spite of the many market failures of the fossil-grid paradigm the literature shows that the electric grid networks function relatively well for urban and rural areas of developed high-income countries. With the grid having no substitute in the advanced countries, the literature also shows that developed countries like the USA can probably replace fossil fuels with renewable energy systems to be delivered through the same grid, though at a somewhat higher but affordable cost due to their high incomes. In the last century when the off grid-technologies were not mature enough, the rural grid was the only option and USA style rural electrification was ported to mid-income and poor rural economies of the world. Rural electrification flourished in Communist China to cover more than 99% household through small scale decentralized townships and hydropower systems. But democratic India had no commercial success of the centralized grid network to deliver fossil energy to far flung impoverished villages and achieved less than 50% access.

The commercial competitiveness and economic failures of the fossil-grid system were discussed in relation to low income rural India. The grid, though dominant and subsidized is not very successful in rural electricity markets. On a more detailed level, I showed that the existing non-transparencies and the anti-competitive nature of rural grid management have led to investment, operating, and usage inefficiencies in the rural grid supply chain. These inefficiencies result from the political need for the rural grid subsidies. Inertia makes the subsidies and political interventions hard to remove. Besides grid subsidies, another example is kerosene subsidies which serve no useful purpose in India but have been politically impossible to remove for decades (Shenoy 2010). Rather the rural areas remain in darkness. SPVs, which could have brought light, face an uphill battle (Kar and Rukis 2004). Apparently there is wide spread misunderstanding that the rural electrification subsidies and rural grid monopoly are unavoidable now or in the future. It is also hoped that these subsidies can be supplied through cross subsidies from the profitable urban and industrial consumers. However, I showed in section 2-2-3 that the data and evidence in the Indian power sector from the last two decades suggest that cross subsidies are not sustainable or able to support more grid supply. The recent experience is of ballooning losses and administrative mispricing of electricity, leading to the choking off of funds to the otherwise profitable urban power sectors. Further, government investments in an outdated rural subsidized grid might be inhibiting emerging competitive and innovative off-grid SPV technologies.

Now with the public opinion swinging towards green and renewable energy, the SPV-grid is being suggested for India as a panacea for climate change, recent high increases in grid prices, fossil fuel scarcity, and pollution control. I argued in section 2-3-3 that an SPV grid with high cost SPV electricity subsidized and fed through the grid will compound the problems of subsidies and anti-competitive outcomes with the potential to become another economic disaster as we saw in the Indian power sector in last decade. A grid connected large scale SPV systems would carry with it moral hazards and adverse selection, which have already mired the Indian grid with revenue and investment deficiencies. I reviewed the literature to argue that this porting of fossil-grid or renewable grid to India is not economically viable and may be technically inappropriate. They will not remove the essential rural problems of low access and high costs. Still, the grid is being popularized through the same top-down promise of huge unsustainable subsidies in a poor economy.

I argued in section 2-4-3 that problems are best avoided through off-grid renewable and SPV technology, which is ready to meet the challenges of rurality and poverty. The rural areas have many non-electric off-grid substitutes such as kerosene, diesel, biogas, cow manure, and biomass. The review then presented the emerging scenarios of alternative clean SPV technologies; how these fringe suppliers today are emerging from the background of a dominant fossil-grid paradigm The review also highlighted the benefits of local availability, small-scale demand, competition, and conservation compatibility of renewable energy systems, again with a focus on rural India. Integrated into this discussion was the information drawn from the literature on off-grid technologies like SPV for lighting, pumping, and ICET for community health, education, entertainment, and biogas/biomass for cooking, production, and transportation.

There will be no inhibition to market competition, innovation, efficiency in off-grid SPVs and there will be no non-technical, externality costs of energy regulation, emission, and ecological disasters. In order to prove a subsidy free off-grid SPV market exists and no such rural grid market exists I will use the demand and supply models and the cost data as explained in the literature review. Although solar electricity consumption requires expensive battery support, the battery-based systems are nothing new in India. Indian urban homes use battery-inverter systems for their minimum basic needs of lighting/TV/fans. They often store 10% of their daily use in a battery. Thus, battery inverter systems are inevitable to meet some part of the daily load of both poor and rich households, community centers, schools, health posts in rural areas. Batteries do not increase the economic attractiveness of the grid but increase the value of efficient and portable SPV devices. Off-grid and modern renewable energy from the biomass and SPVs could be better options for providing access to the non-electrified remaining half of rural India.

I conclude this chapter with a summary of the benefits of off-grid SPVs, their merits and demerits as shown in Table 2-10.

Table 2-10 The advantages and disadvantages of the grid and SPVs

	Urban Grid	**The Rural Grid**	**Off-grid SPVs**	
	Advantages of Grid Network	**No such Advantages**	**Technology to Match the Grid Advantages**	**How does village community culture help?**
1	Diversity through network wires	Not much diversity with all lighting loads	Diversity in portability of the RET systems with small battery storage running efficient appliances, pumps	When there is surplus battery charge in one home, it can be rented to another with a deficit.
2	Lights "Always On", Weather-proof as back up provided by grid	Not storm proof	Battery backup, conservation, demand response, and "Anytime Light" and "Anywhere Light"	Weather tuned culture can continue with high daytime activities, better weather forecasting can reschedule work routines to minimize battery use.
3	High scale of operation	Low scale of operation	SPVs solar heat and bio energy have low scale economies, good for low rural demand	The villagers already use these fuels inefficiently switching technology but with same input relatively easy and risk-free
4	High fixed costs get spread out and cross-subsidized without a tax	Subsidy not efficient; not many high income customers to cross subsidize and attract investments	Cost of social expenses in health, education, and production subsidies can support the solar PV systems	Rural areas needs the social amenities and education and health at the community level which is less expensive
5	Utilities can raise finance at lower costs	Government loses in the rural grid, no finance to even meter consumption	Can be financed based on the "beneficiaries and polluters" pay principle	Rural customers have high willingness to pay bit less ability to pay
	Disadvantages for Grid		**No Such Disadvantages for Off-grid SPVs**	
1	Requires wires not very portable		Portable lanterns, fans, pumps	
2	Polluting and emission with fossil fuel		No emission or externality costs	
3	Climate impact of fossil fuel		No carbon foot print	
4	Adverse selection when rich and politically connected get access first, may not pay, but consume more		The subsidies can be directly paid to the users through loans, one-time grants, customer's education, services and marketing support.	
5	Moral hazards of government ownership, principal agent issues in regulation, adverse selection of bad contracts		The users take control and feel responsible to what they own.	
6	No competition and so no innovation, advances in technology or cost reduction		Competition helps innovation, cost reduction and products varieties to meet each needs.	
7	power and asset theft, storm, vegetation related fault propagates and perpetual subsidy		No theft of energy or assets, such costs internalized by the customer.	
8	Safety of the rural grid questionable		Less safety issue in 12 V systems	
9	Poor collection efficiency in India, require high cost meter, inspection, and billing systems.		Collection is a big issue in rural India, but can be managed through security of the devices, local credit monitoring, and micro financing.	

CHAPTER – 3

THEORY AND METHODOLOGY

In this chapter, I will develop the theory for my four research questions, which are repeated as follows:

Q1. Is off-grid SPV electricity cheaper than grid electricity for the rural poor in India?

Q2. Can off-grid SPV electricity or grid electricity be subsidy free for the rural poor in India?

Q3. What are the break-even incomes for the grid to be cheaper than off-grid SPVs?

Q4. Can this break-even income and consumption be reached in the future for the electricity grid to be subsidy free?

In order to establish that off-gird SPVs can be cheaper and subsidy free but the grid cannot in poor Indian villages, I will develop theoretical cost curves and the village household demand model already indicated in the literature review. I will first present cost models for competitive cost analyses (Q1), then develop the theory of demand for income threshold analyses (Q2 and Q3). Q1 to Q3 will require static analysis of the current state of competition. Q1 requires only the long run marginal cost curves to be compared, Q2 and Q3 will require the demand curves to be compared with the supply cost curves developed in Q1. Then I will describe a dynamic dominant firm model to predict future competition in 2020 (Q4). In the dynamic dominant firm model of Q4, I will introduce the time element and refute any claim that the rural grid can remain the primary dominant commercial energy with SPVs only in the competitive fringe. No previous study to my knowledge has included all of these supply and demand side factors when comparing the rural grid to renewable SPVs. To this extent, my research is likely to be a path breaking initiative to introduce a theoretical and quantitative analysis to study the dynamic interaction of grid verses off-grid renewables.

3.1 Theoretical Framework for the Research Questions

For a long-term market equilibrium to exist, demand and supply must meet. Customers must be willing to pay a price that will recover the long-run marginal costs of supply. Without such a common meeting point, a market equilibrium does not exist without subsidies. Thus, it is necessary to determine both cost and demand functions to see if an equilibrium exists now and in future. I will first explain the static analysis for Q1 to Q3 in sub section 3.1.1 and then the dynamic analysis for Q4 in subsection 3.1.2

3.1.1 Demand and supply models for static equilibrium analysis (Q1-Q2-Q3)

The answers to the first three questions require the modeling of both the supply cost function for the grid and SPVs in rural areas. I will also determine the cost curves of kerosene as it is a widely used electricity substitute as well as supplement for rural lighting when and where the grid power is blacked out or is not available.

Electricity demand estimation requires price and income as independent variables. The demand shifts from increasing income over time or across the various classes in the same time period has special significance in this research. Depending on the income level, the demand function can be plotted as D_L or Dr or Dh for very low, rural low and high demands against the cost functions of both the rural grid and SPVs as shown in Figure 3-1.

The supply curves of the SPVs (Ps) and subsidized kerosene (Pk) are also shown in the figure as two straight horizontal lines. Neither the off-grid SPVs nor the off-grid fossil fuel (kerosene) have any significant scale economies and both can be delivered in small scale in a competitive market. Due to their modular nature of being delivered in very small sizes, they can be sold at affordable costs with no subsidy, as shown in the figure for all the downward sloping demand curves, including the very low demand line D_L.

LACr is the long run average cost curve of the rural grid, which buys electricity from the central grid network. The rural grid may or may not meet the demand lines D_L or Dr. Dh, the line on the extreme right, is a demand curve for the rural grid for a very high income customer. When income is high, theoretically, there is no problem in getting a subsidy-free supply of grid electricity as Dh can effectively meet the supply function at or close to optimal price. Here the price Ph is also cheaper than Ps. Research question 2 will be answered once actual demand is estimated. If income is very low like D_L, we will not observe any demand supply equilibrium and will conclude that the grid has to be subsidized.

Further, if demand and cost meet at all and equilibrium is possible, there is no guarantee that equilibrium will be efficient. For example, any price above Ps is an irrelevant grid equilibrium and Pr has no practical value in a competitive market where households have access to SPVs at a lower price. Thus, Ps sets the absolute limit of how much a grid firm can charge to rural customers in a competitive market of free entry and exit. Ps becomes the long run average cost of the rural electricity market when it is below the grid.

Do, the solid thick demand curve in the middle of Figure 3-1, represents the threshold income where the grid cost can be competitive with the SPVs and be subsidy free. Below this income level, grid electricity is more expensive than SPV electricity. Above this income threshold, the demand is beyond Do making the grid not only subsidy free but also cheaper than SPVs. In all cost studies and popular literature, when the point is made that grid power is cheaper, the implicit assumption is that the consumer is using enough power and has enough income to pay for it at Do and beyond. This threshold income condition will be found as the answer to the third research question Q3.

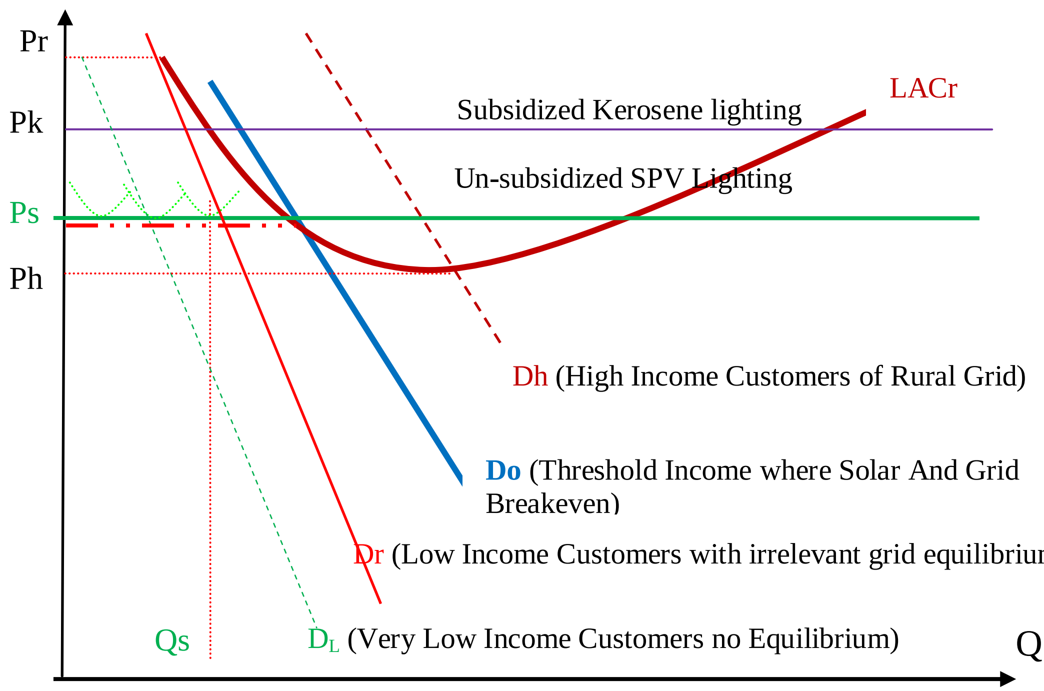

Figure 3-1 Equilibrium of SPVs for poor income, where grid has none

While the answer to the first three questions can be dealt with by using the static equilibrium analysis from the demand and supply equilibrium, the answer to the fourth question requires a dynamic dominant firm model.

3.1.2 Dynamic "dominant firm model" to estimate the future equilibrium outcomes (Q4)

The dominant firm is a monopoly where competition exists from the fringe suppliers and the dominant firm is aware of its supply cost curves and tries to accommodate competitors if it cannot drive them out by very low marginal cost pricing.

But this monopoly is possible only if the supply cost is below the demand function of the consumers as shown by the Dh in Figure 3-1. As such a high demand exists in the urban electric grid market, the dominant monopoly is regulated. This demand profile does not exist in rural India for monopoly pricing to occur. Thus only a regulated rural grid often dominates in rural India not as a profit making entity in a free market place rather as an extension of the government to create a market where none exists. We will describe such a rural market also as a regulated market where the prices are also severely regulated downwards to serve the rural poor.

a. Residual demand is too low for the rural grid to survive but helps SPVs

Bio-heat contributes to grid failure because it takes away demand causing the grid to lose its economies of scale. However, this demand reduction aptly helps the SPVs, as a crucial high quantity need for electric heating will not have to be provided through expensive solar electricity. The availability of such low cost rural off-grid bio energy has been established in the literature but because the primary focus of this study is on SPVs, I will not quantify its availability here. But its role in rural energy provision will be recognized later in Chapter 6. The remaining electricity needs for ICET, lights and fans are easily provided through SPV systems as the residual demand represented as RD in Figure 3-2. The cost curves from the competitive markets are shown as the horizontal lines in this figure and the regulated rural grid cost curve as LACr, which is low only if the grid demand is high such as with urban demand Du or high income demand Dh. The urban and high income customers cannot use off-grid bio energy due to high logistic/transportation costs, taste, or much higher value of the customer's labor time to process biomass for cooking and heating.

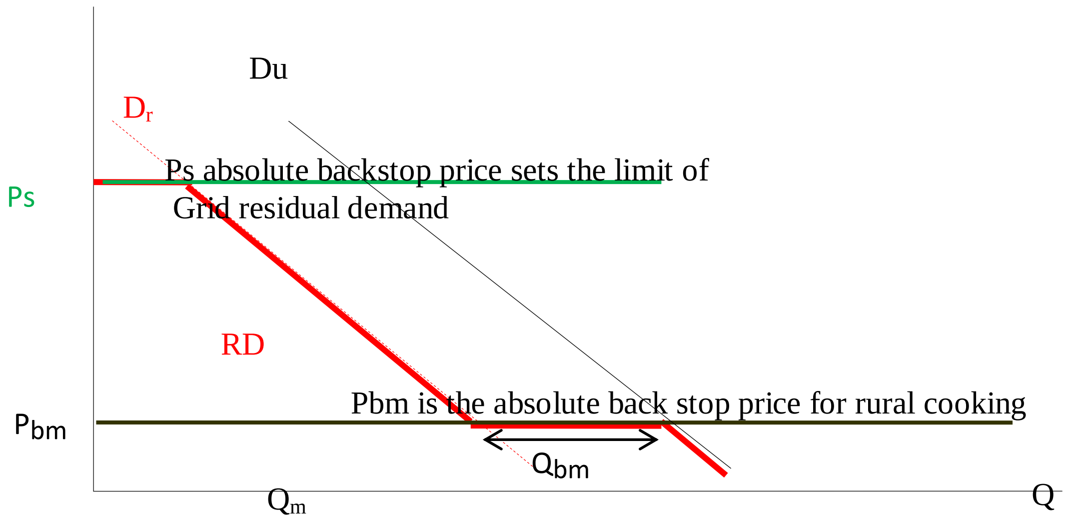

Figure 3-2 Horizontal supply curves of off-grid renewable and solar PV as back stop

Electricity is often seen as a biomass substitute in a few rural rich households that have a higher labor value and wish to avoid the hidden biomass cooking costs of smoke and preparation time. However, TERI (2003a; 2004) shows that average customers will use biomass, or at best, biogas fuel, which is less drudgery prone and non-polluting. Such biomass and biogas substitutes are not available in urban areas.

The thick red line is the residual demand (RD) for the grid after the competitive SPV suppliers are subtracted at price Ps. The electric demand curve Dr will move to the right only if electricity can be supplied at a cost lower than the already low cost of biomass used in rural cooking. As very few Indian villagers use electric heating and almost everyone uses biomass even at 3cents/kWh, the effective cost of electricity for biomass heating and cooking must be less than the 3 cents/kWh. The studies by Dutta et al. and others have in fact shown that the heat energy for cooking costs less than 3 c/kWh. The observed demand curve for electricity will be Dr. Only if the price of grid electricity falls below the biomass price will the cooking and heating energy, Q_{bm} at P_{bm}, add up to the currently observed demand curve Dr in the village. From the literature review as well as from the JABA village grid price, we see that 3 c/kWh could be a market choking price for heat. As the heat is almost 70-80% of all domestic energy and assuming 4kWh/day and 120 kWh/m, 3c/kWh still could be a high enough price to be affordable for many with access to electricity. The monthly cost of $ 3.6 only for cooking food is definitely high, when monthly cash income is less than $100.

The urban grid firm can exercise some monopoly power with higher urban income and fewer low cost substitutes yielding demand for electricity Du. The residual electricity demand for a rural grid with biomass availability factored in is shown with another horizontal kink in the lower part of the curve RD. The grid firms with continued dominance in the urban domestic market during the last century do not have the same advantage in rural poor markets.

The rural grids were also challenged by off-grid kerosene which is highly subsidized. Diesel engines using subsidized diesel fuel are still popular for irrigation and rural production markets, as the rural grid, where it exists, is very unreliable. There is no doubt all these subsidies are given to less efficient off-grid fossil fuel in addition to the centralized, large-scale fossil-grid, as they are still considered the must have default supply for want of reliable and quality power in rural areas. This perpetuates a double jeopardy -- an unreliable and unproductive rural grid combined with massive subsidies, pollution and inefficiencies.

b. No market-clearing price for grid electricity in rural homes: Low residual rural electricity demand verses high LACr even in 2020.

As we have already dealt with the theoretical aspects of the static demand and supply for both the grid and SPVs, I will now turn to study the dynamic dominant firm. The dominant firm theory uses the concept of residual demand developed in the literature review (Figure 2-13) and is shown more completely in Figure 3-2 as a two period equilibrium. Solid lines represent the present condition and dashed lines the future. During the future period t, the solid residual demand for poor customers and LACr moves to the dashed lines for moderate income customers and a LACr' with higher grid costs. The figure suggests the emergence of the future SPVs as a dominant firm at the cost of the grid even if the increased income over time will make electricity demand move outwards.

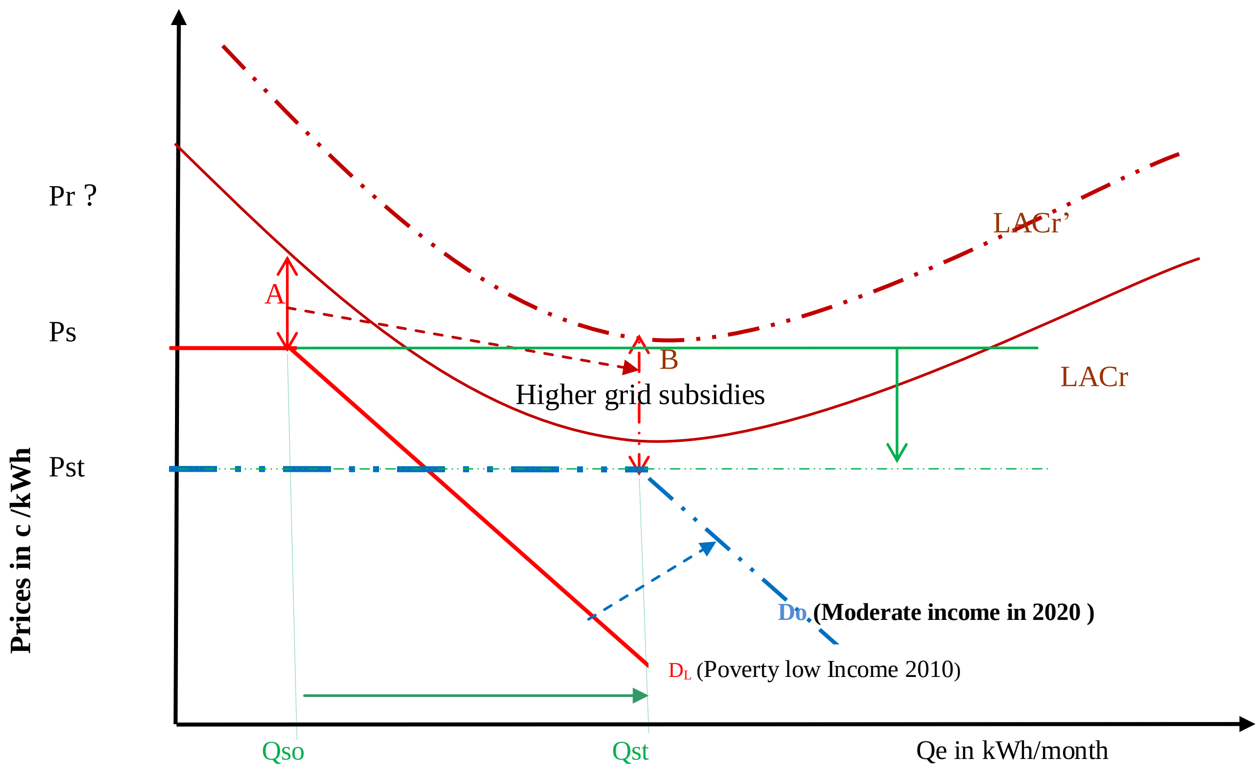

Figure 3-3 Rural dominant grid showing its decreasing viability of and increasing economic supply of SPV Horizontal supply curves of off-grid SPVs as a back stop

Source: Author's depiction of rural residual grid demand (biomass omitted for simplicity to limit the scope of this study, though not very difficult to model).

To find the equilibrium condition, income is a second independent variable that shifts the demand function. In the rural electricity market, where income is already low, the traditional dominant firm analysis fails to account for the lack of a demand and supply equilibrium for grid electricity services. The government uses subsidies (shown as A) to prop up a market that would not otherwise exist. This model can easily show that without subsidies, the theoretical rural market for electricity is dominated by SPVs, which have a proper demand and supply equilibrium shown as the solid lines red demand and green SPV supply. This equilibrium sets the marginal clearing price of electricity, which is below the higher marginal cost of the rural grid. The current market equilibrium is shown as Ps, Qso.

But in the future the marginal electricity price and equilibrium quantity will be at Pst and Qst as shown in the meeting points of the dashed demand and supply lines of Figure 3-3. The PSV supply has come down to Pst and the poor household's demand has moved outwards from D_L to Do. In the meantime, due to the many externality costs LACr might move to LACr' making the long run grid cost not only above Pst but also more prone to subsidies. The need for subsidies, as shown in this figure, has grown from A to B and is clearly not a desired outcome. Thus, I will show in Q1-Q3 that SPV supply and poor households' demand is dominant now in 2010 and will continue to dominate in 2020 in Q4.

After presenting the theoretical construct to answer the four questions, I will now discuss the methodology of developing each of the curves more completely below starting with the definition of the household market for which these curves will relate.

3.2 Market, Cost and Demand Curves for Rural Dominant Firm

In this section, I will explain how to derive the cost and demand curves for rural household electricity services as well as the average cost of the rural grid, LACr. I will develop my analysis at the household level. The small consumption for the very poor in Indian villages will be described and made clear through the case study of an electrified village in chapter 4. Although I will later show that SPVs can adapt to such low levels of consumption, the grid will be at a disadvantage because it requires a minimum size of load and a minimum number of consumers with enough incomes to pay its fixed costs.

In order to answer the first three research questions as depicted in Figure 3-1, I will develop the cost and demand equations of the electric grid and the cost of the solar photovoltaic technologies. The meeting point of the demand and cost function will determine the subsidy free electricity solution for rural households. I will show that there will be no subsidy-free solution as the rural incomes of most rural households are very low and their demand function is as represented by D_L. If a subsidy-free solution exists for only a few high-income households, the grid cannot be expanded for only those few households. Thus, the average income of the households must reach a minimum threshold. In the average Indian village, household income was below $100/month in 2009. In eastern India, home to the highest proportion of un-electrified households, the average income is much lower. Over 90% of households in the Orissa village have incomes below $100/month. I will find the minimum income for a subsidy-free grid as the answer to the third research question. The fourth research question will answer whether such a subsidy free grid will be achievable by 2020. If the villages do not have a high enough number of households with above threshold incomes, grid suppliers will be better off investing their valuable capital and skill in the profitable urban areas with higher returns at lower risks.

3.2.1 Conventional fossil-grid costs

The fossil grid costs that will be used are the long run marginal costs of the rural grid for the supply of electricity and kerosene for lighting.

a. The long run marginal and average costs of the rural grid: LACr

For a proper comparison, I should consider the long run marginal costs (LRMC) of the grid with the SPVs. Our LACr for the rural grid is this LRMC as most of the electrification in India we are concerned about is new. This study will use the opportunity costs for electrical energy from the larger nationally integrated competitive wholesale market called North-East-West Interconnect (NEW Grid). These marginal energy costs are represented as a horizontal supply line as electrical energy in this wholesale market is liquid and the capacity of generation assets is fungible. However, there is no such market where distribution services are fungible and can be bought and sold. To reflect the most current opportunity costs for the distribution system, the ongoing nationwide RGGVY program provides the cost data for the physical distribution assets. Therefore, the average incremental distribution costs of the recent grid expansion could be considered as a proxy for long run marginal grid distribution costs. The ADCr will be calculated by annualizing these investment costs, adding the annual operating costs and then dividing these costs by the annual electricity consumed. These costs can also be computed using consistent monthly data and I will use such monthly calculations.

The long run marginal cost is composed of the average variable energy costs and the average fixed capacity costs. I will use the long run average of capacity costs of the new distribution grid as the average capacity cost ADCr. LACr is thus composed of two parts, the average variable commodity cost of electricity in the wholesale power market, denoted as the loss adjusted grid energy price Pg and the average fixed distribution cost of delivering that electricity to the customer (ADCr).

Grid electricity is bought in bulk during the peak hours from the centralized wholesale market to meet the rural domestic loads. Then the electric utilities must make adequate investments for the capital and O&M (operation and maintenance) of the distribution fixed assets. These fixed assets are long rural HV (high voltage) substations and primary feeder lines, LV (low voltage) distribution transformers, and secondary distribution lines. Besides, the customers must have their own investments, operation and maintenance expenses for service lines, meters, house wirings, and domestic safety and protection systems. ADCr will depend on the investment cost for each customer, which in turn depends on the customer's electricity consumption in kWh/month (Qr) and the capacity reserved, which is based on the peak capacity demand in kW (Qc). I will first determine the average investment cost per customer and annualize these upfront investment costs to determine the ADCr as a function of Qr and Qc.

$$LACr = Pg + ADCr\ (Qr, Qc) \qquad (3\text{-}1)$$

b. The fossil fuel (cost of kerosene) Pk:

I will show that kerosene is a fossil fuel supplement to the unreliable and scarce rural grid in rural India. Expensive kerosene delivers scant evening light along with low cost electricity in various combinations in rural homes. I will use the village ration shop price of kerosene to derive the electricity equivalent price Pk in cents/kWh. The equivalent price Pk will be computed with the assumption that villagers use a kerosene lamp equivalent to 5W incandescent bulb. The subsidized rural grid electricity price Pa will be the subsidized grid price in the village case study.

A weighted average of their costs can provide a range of price variables for the effective electricity price. This has not been done before, as there is hardly any price variation in the electricity supply to rural households, which is subsidized and has been kept constant for many years. This approach to deriving a linear regression model for rural demand is another contribution to the literature.

3.2.2 Fringe supply cost drivers

a. Renewable heat supply

Biomass or solar heat energy supply is also assumed to have a horizontal supply curve at significantly lower costs than the lowest average grid cost. In spite of the governments' subsidies to grid and petroleum fuel, biomass is used in primitive forms with no cash outlay and little competition from the grid. The biogas resources at lower levels of income can be supplied locally at the same average cost, which is also equal to the marginal cost with no scale economies. This demand for heating and cooking energy can vary from a fixed quantity as high as 4-6 kWh/day per family at a fixed biomass price of Ph = 2-3 US c/kWh based on the studies of the Lenzen (2009), Cust (2008), Singh (2006) and Chaurey (2004). This low cost biomass heat supply will be replaced by electricity only if the electricity price is lower. The empirical demand for electricity will not include heat as no one in the Indian village survey uses electric heat.

b. Renewable Electricity Supply

A flat rate of 20- 40 cents/kWh for SPV based devices, reflecting only the electricity energy component of the costs have been reported in the literature. I estimated the actual average costs based on the actual market data near the case study village in 2008. My estimate is around 38 cents/kWh and higher than the estimates by Cust et al. (2007) and Banerjee (2006). No supply quantity limitation will be expected as the rural demand is low but the rural supply could be large due to better land availability to capture sunlight. For my cost projection into the future, I will use a learning curve effect of a 10% reduction in cost for each doubling of the global production of SPVs rather than the 20% cost typically reported in the literature. As in all my computations, I will be conservative in the sense that my assumptions will never be biased in favor of SPVs.

c. There will be additional costs of the balance of systems (BOS).

BOS costs of the devices such as battery and charge controllers/inverters are common with the rural grid, which is also intermittent, as is solar. The high costs of solar devices are compensated for by the efficiency of the end use and the built-in energy efficiencies over the life of the device. For example, solar lighting is best used through CFL or LED, which are more expensive than incandescent bulbs, but these lamps are safer, use less energy, are less polluting and have a longer life that pays off many times in their life time (DOE, EERE 2007). The solar lantern is a portable ICET device that can be used "anywhere" and "any time" not only for lighting, but also for charging a separate/built-in radio and cell phones.

In Chapter 5, I will explore the first question: whether the grid is cheaper than off-grid SPVs when only the pure economic costs are considered, and under what usage conditions the grid is cheaper than SPVs. The first question will not require an estimated demand curve but will be based on pure costs to show when SPV electricity is cheaper and if the grid is cheaper for the 30 kWh RGGVY target. The last three questions look at the grid or SPV competiveness with respect to demand to see if SPV electricity can meet the poor villager's demand without subsidies now (Q2), what should the threshold income of poor villagers be to make grid electricity subsidy free (Q3) and can the grid be subsidy free by 2020 (Q4). Thus an estimated demand curve is a core piece of this thesis and the theory and model behind it is presented below.

3.2.3 Modeling a log linear demand for the rural village households

Electricity demand for homes is derived from the demand for lighting, fans, TVs, electric appliances and gadgets (ICET) for health, education, lifestyle comfort, and entertainment (Barnes 2002, Choynowski 2002). More evidence will be collected to see the nature of such demand in the next chapter on the case study. I will adopt a semilog demand Equation 3-2 from Choynowski with an added income term to make the rural demand curve practical for our poor households. With the addition of the income variable Y, the semi-log relationship between quantity Qe and price Pe as applicable for household demand is given by

$$\text{Ln } Qe = a + bPe + cY. \quad (3\text{-}2)$$

The above semi-logarithmic demand curve approaches the price axis asymptotically at lower levels of household consumption. This reflects a poor household's willing to pay a high price to consume some amount of electricity. Similarly, by assuming limited consumption at even a zero price, we are retaining the property of a straight line demand curve that limits the absolute amount of the electricity that will be demanded based on the number of appliances a household can buy. This amount is very small for a poor house as they will be only buying a few light bulbs. Where Qe is the electricity demand in kWh, Pe is the price of the electricity in c/kWh, Y is the monthly household income USD/month. The parameters a, b, and c will be determined from the regression of the village income and energy-use data. The kerosene lighting cost will be converted to an equivalent c/kWh to make lighting costs comparable with the cost of grid electricity as suggested by Barnes and Choynowski. In my study, I will use the weighted average prices of electricity and kerosene for the demand estimation from Equation 3-2. As indicated before, this will be a unique contribution, as no one, to my knowledge, has done such a weighted averaging of prices to get a larger number of data points for the price variables required for more accurate regression modeling demand for light.

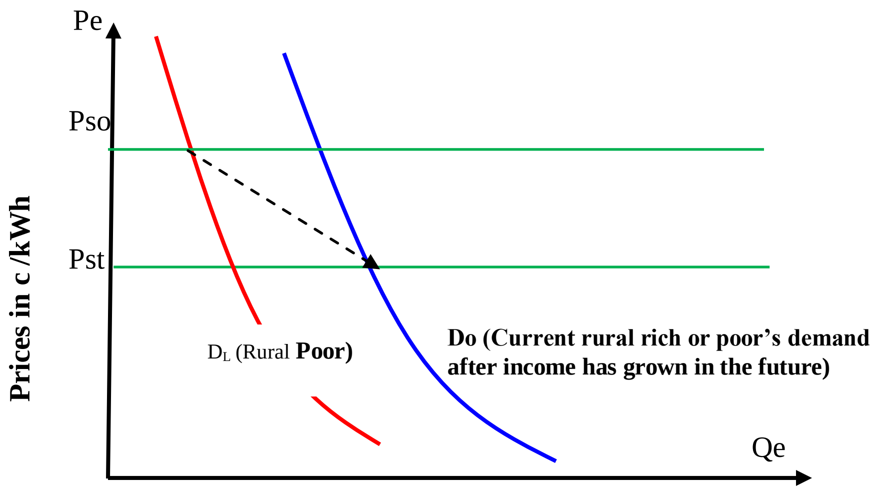

Figure 3-4 Log-linear electricity demand model touching Q axis and outward shifting at higher incomes

3.3 Rural Dominant Firm Model with Off-Grid SPVs

I will now use a special case of the dominant firm model in order to find a formal answer to a specific question: Can the grid be subsidy-free in a dynamic setting of emerging renewables by

2020. For incomes below a certain threshold, the grid is inferior to the renewables and is in fact theoretically not a dominant firm. The study will focus only on residual demand for energy after household heating with biomass has been taken out to infer whether a demand and supply equilibrium can be obtained.

I will now describe a learning curve effect and document that, learning will cause costs to continue to fall. Then I will show an upward shift in the potential demand might not create the necessary demand supply equilibrium as the residual grid demand after the fall in SPV prices could be still below the average supply cost. I will show the rural grid can only exist now and in the future through subsidies with high average costs of supply and poor demand. In the long-run, if grid costs increase as expected and the emerging technology continues to become cheaper, it could be in direct competition through market diffusion. I will then argue that the dominant firm will no longer be dominant. This cost reduction might have already been reached and costs will probably continue to fall further in the future. This is explained through the dashed line in Figure 3-5 where the new equilibrium price condition for SPVs is lower than the grid average cost curve and hence is a credible threat for the rural grid. The residual demand curves, which are partly horizontal on the upper portion and partly semi-log on the lower portion, are always below the LACr, which is assumed constant in both cases.

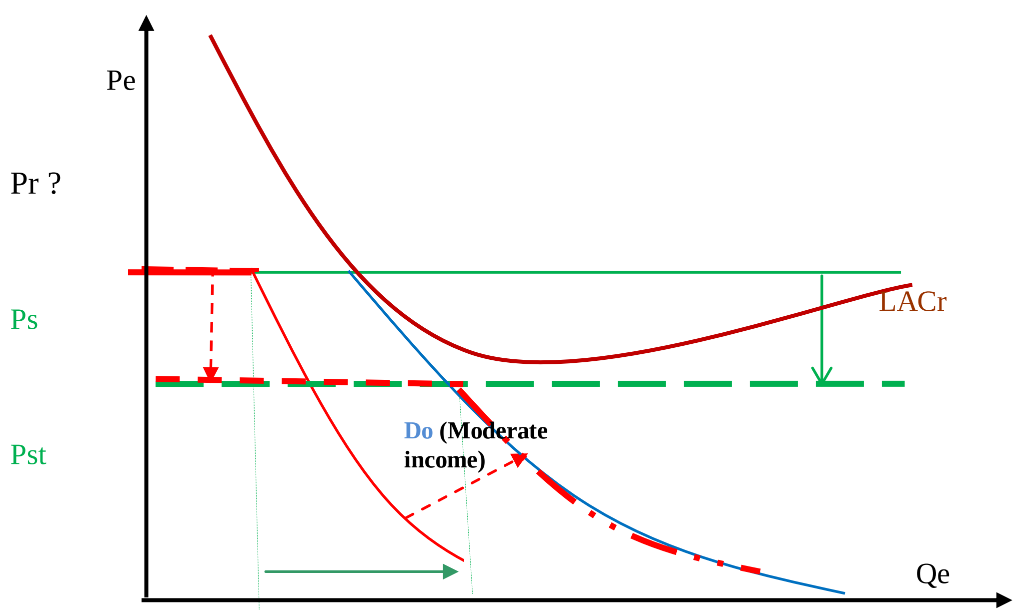

Figure 3-5 Rural Dominant Firm Model showing decreasing viability of grid supply and increasing SPV supply (biomass omitted for simplicity to limit the scope of this study, though not very difficult to model).

3.3.1 SPV exogenous cost -reduction and increased income will drive a competitive market

The learning curve is generally used to explain how cost reductions are expected in high cost SPVs, energy efficient appliances, and devices like LEDs, electronics, and DC motors. Figure 3-4 includes the learning curve effects on the cost reduction of SPVs. These learning curves are being observed worldwide in the new products markets, not only for SPVs, but also for inverters, efficient LED lighting, and ICET devices and gadgets. These technology led cost reductions are in direct contrast with the scarcity and externalities costs of fossil fuels. Such reductions already have and will continue leading to the growing competitiveness of SPVs.

Table 3-1 The summary of the learning curve and price reduction of SPV modules in the past

SPV system	Geographical area	Time period	PR	Source
SPV modules (crystalline silicon)	Japan	1979-1988	79%	(Tsuchiya 1992)
SPV modules	USA	1976-1988	78%	(Cody and Tiedje 1997)
SPV modules	USA	1976- 1992	82%	(Williams and Terzian 1993)
SPV modules		1981-2000	77%	(Parente et al. 2002)
SPV modules		1968-1998	80%	(Harmon, C. 2000) (several different data source)
SPV modules (crystalline silicon)		1976-1996	84%, 53%,79%	(OECD/IEA 2000)(based on the EU atlas project and Nitsch 1998)
SPV modules	Germany		app. 90%	(Schaeffer et al. 2004)
SPV modules	the Netherlands		app. 90%	(Schaeffer et al. 2004)
SPV modules	Globally	1976-2001	75-80%	(Schaeffer et al. 2004)
SPV BOS	Germany	1992-2001	78%	(Schaeffer et al. 2004)
SPV BOS	The Netherlands	1992-2001	81%	(Schaeffer et al. 2004)
			74%	Maycock 2002
SPV modules		1976-2001	80%	Strategies Unlimited, referred to in
		1987-2001	77%	Schaeffer et al. 2004

Source: Experience curves developed for PV (EC 2005).

Therefore, over time, the cost curves for SPVs will fall downward while the grid cost curves will shift upward. These shifts are shown in Figure 3-3. After fitting the most current data available in 2008-9 to the cost and demand curves in the dominant firm model shown in Figure 3-2, I propose to use the predictions of cost reductions in SPVs from European Commission (EC 2005). Their numbers in Table 3-1 show the Progress Ratio (PR), defined as the reduced price in each doubling of the global production reflecting the learning or experience effects varying from 78% to 90%. This is also demonstrated using the learning curve parameters from the studies done by IEA, World Bank, and the PV industry. The overall impact will be observed, seeing how the reduced SPV price will lead to higher fringe supplies, and reduce demand for the dominant grid as shown by the arrows in the figure above. This will increasingly threaten the government monopoly, which will lose future market share.

3.3.2 The increasing grid cost cannot make the demand supply meet in the future

The cost reduction in the grid environment is harder than for SPVs due to lack of scale in rural areas, lower demand for poor quality electricity services, expected fossil fuel scarcity, lack of incentives to reduce costs, increasing pressure to internalize externalities, increasing likelihood of carbon pricing, and maturity of the industry. Though the grid suppliers will demand more subsidies, it will be politically difficult and economically absurd and inefficient when the SPVs are cheaper, subsidy free, cleaner, and can be delivered in a competitive market.

3.4 Varieties of Data Sources and Lack of Accuracy Demands a Conservative Analysis

Data on the costs of various renewable and fossil fuel technologies in grid and off-grid renewable systems are now available in many refereed journals as well as Indian Government and international aid agencies sources. Though international comparison of data on prices and costs of most of these technologies are hard to compare and never constant over time, they vary over a narrow range due to tradability of inputs in competitive markets such as for coal, power equipment, and SPV systems. The labor and locally made heavy material prices are lower in India and help both rural grid and SPVs in lowering the installation and non-fuel operation costs. I will briefly describe here the sources of information, and indicate why I take a conservative approach in favor of the grid and against off-grid SPVs.

3.4.1 The fossil grid cost variability

Costs have wide variability because of plant location, climate and weather conditions, as discussed before. For example, the cost of generation from coal plants located at the mine mouth will cost less than the cost of generation in load centers as the coal has to be transported a longer distance. The fossil-nuclear-grid based electricity costs also vary with environmental and safety regulations that vary across the country depending on the political forces on internalization of the costs of pollution control, safety, and penalties for no performance or damage. The vintage of the plant is also important as many old plants are already fully depreciated making the average book costs very low. In addition, pollution control measures are not necessary where grandfathering of old polluting assets are allowed. Thus, pollution costs are not internalized and do not enter the generators' cost equations. As the marginal costs are not reflected in the prices, the average prices vary from the utility to utility. The real-time pricing of electricity, which requires constant metering, has only recently being introduced in many parts of the USA, is hardly used in developing country electricity pricing. Rather average grid costs are typically used. I will avoid such cost differences by taking marginal cost from the competitive wholesale power market prices for electricity. I will use the Indian short-term power market prices, which are now more transparently available and more clearly reflect power scarcity effects on the grid marginal energy costs. I will also add the distribution costs (ADCr) to the loss adjusted wholesale costs to find the delivered cost of the grid power to be compared with the solar PV costs. The incremental average distribution costs from the current RGGVY program of rural electrification will reflect the current marginal distribution costs. I will assume a cost lower than the currently planned RGGVY investment to show even a village grid that is close to the central grid could still be inferior. The marginal cost data of transmission and negative externalities will be neglected for the same reason.

3.4.2 The off- grid SPV cost variability

The data available for renewable energy technologies vary a lot because of the numerous financial and operating parameters, discount factors, local market prices of SPVs, and balancing devices such as chargers, inverters, and batteries, which are in many cases integral to the SPV systems. The financing assumptions and O&M factors across countries cannot be generalized because of the high cost of capital but the low cost of surplus rural labor in India. The location of service is a very important factor that will give varying cost estimates for off-grid systems as well as grid supply costs as indicated by World Bank (2008). I propose to use conservative estimates for the local retail market prices of SPVs which are much higher than the on-line retail or wholesale costs of these solar panels and ignore the costs of battery-inverter systems as these later costs are assumed equal for the intermittent supply of both the rural grid and SPVs.

Also, the costs of SPVs vary from 18 c/kWh to 80c/kWh for battery based portable systems (Singh et al. 2008). While the costs vary within a wide range, the applications also vary from utilizing a portable light to charging a cell phone or charging and running a laptop. Further, the transportation, after-sales service, and maintenance training are the variables that are based on local situations. When a villager is already paying 90 cents/kWh for lighting through kerosene and $2 per disposable battery pack to listen to the radio, the economic value of portable electricity is high for their mobile lifestyle and farm jobs during the days and for nightly production and entertainment when the communities do not have evening lights. Often production and community activities are located outside small huts for lack of private or community/production centers. Houses are small, but farms and backyards are larger; thus portable systems will be more helpful than stationery grid based lights.

While solar costs have decreased recently, I have still used the cost of the SPVs as available in the local market in Orissa from the 2002-2007 periods at the retail level where the competition was yet to develop in full scale. The costs of the grid are based on large-scale purchase by the government. Similar large-scale bulk purchases or competitive rural marketing can reduce SPV costs and the value of SPVs in rural areas in the future through innovations. This will bolster the argument that the SPVs are competitive even in electrified villages as seen in the experimental village from which data was collected.

3.5 Selecting Dominant Firm to Answer Q4 if Grid can be Subsidy-free by 2020

I presented the theoretical framework of the static demand supply models to answer the three questions of the grid cost is cheaper than off-grid SPVs, if the off grid can be subsidy free, and if not what is the threshold income where the subsidy free grid will exist. These costs will be compared with the cost assumptions of Indian RGGVY planning documents. For a conservative analysis in favor of the grid compared to the SPVs, I will use the lower grid investment costs, lower T&D losses, higher capacity utilization of the rural grid and lower operation and maintenance costs to show that villages close to the existing grid or even electrified villages have grid costs higher than SPVs.

To answer the fourth question whether the threshold income might be achieved in rural India by 2020 and the grid can be subsidy, I used a dominant firm model in a dynamic setting. The dominant firm model in my thesis will be a monopoly grid without market power, as its marginal cost is higher than the price available through the highly truncated demand function. The horizontal supply curve for SPVs and biomass/biogas/solar heat as fringe players will provide a price cap for the dominant firm making the grid non-sustainable. I will use a discrete current period 2010 demand and supply models for a static analysis of the present competitive situation. I will use a continuous exponential growth model to make the model dynamic and forecast the competitive situation by 2020. The dominant firm model will use the data on the recent Indian grid electrification program RGGVY and allocate the costs to each household based on its peak demand. The cost functions thus will be determined at the household level as will the estimated demand function. The village data from the case study will be used to estimate a demand function with price and income as independent variables. The cost and demand functions will be integrated into the dominant firm model. Initially, the rural grid will work as a dominant firm with SPVs as a fringe supply. But gradually, as demand increases, grid costs increase, and

SPV costs decrease with learning, we can expect the dominant grid firm to lose market share. Both electrified as well as un-electrified poor homes will increasingly choose solar electricity.

Now I will turn to a village case study to see how the off-grid SPVs can compete with grid and gather data for cost and demand function estimations for both the grid and SPVs.

CHAPTER – 4

CASE STUDY- DATA AND OFF-GRID VILLAGE DEVELOPMENT

The objective of the case study is to find out if solar PV can provide subsidy-free electricity and meet rural household and community ICET needs. Considering the current strength of local SPV resources and global opportunities of energy efficient ICET infrastructures, I want to see how new SPV energy technologies challenge the rural electric grid in a typical village setting. My study will show that solar technology is least cost, is affordable, and can help villages leapfrog the fossil-grid subsidy age. By getting rid of the rural subsidy obligation for the grid industry, the urban markets can be made economically subsidy free as has been the case worldwide. This is an important contribution to the literature and also has significant practical implication on the delivery of foreign aid, or in the global climate change debate as I will show in Chapter 6. To show that SPVs are competitive, I need to find the capacity and willingness to pay of the villagers. The income and price data from the village will provide the input for demand modeling. Then I compare the demand to costs in Chapter 5.

4.1 Outline of This Chapter

I collected data to understand what type of energy sources to choose and to observe the benefits or problems of the solar electricity. Data on the village's demography, economy, and energy were collected at the beginning of the research in late 2003 to understand the energy consumption, income, household preferences, and whether modern SPVs have any impact on the villagers. The broad outlines of the case study are as follows.

1. Selection of the sample village and data gathering
2. Data analysis at the community, household, individual level
3. Feasibility of SPV electricity for JABA village
4. Implementation of SPV energy based alternate initiatives for meeting the basic ICET electricity needs of villagers:
    - Portable firm and home lighting with the introduction of SPV for lighting
    - Radio, fan, computer, wireless telephone, and internet
5. Study Observations and Analysis

4.2 Village Selection

For the case study, I selected rural areas in the state Orissa in India where I was born and with which I am most familiar. This choice meant I could get resources from my family, relatives, and acquaintances to carry out this project that was expected to continue for at least 5 years. The village Jahangirabad, where I was born, is connected to two more villages, Balabhadrapur and Kalyanpur and all three villages are situated on the bank of a small river (Figure 4-5). I selected the two villages Jahangirabad and Balabhadrapur (here after referred to as one JABA village) both situated on one side of the river. Intensive primary data collection was done in 2003 to understand their energy, income, and quality of life. Although the data is limited to two village hamlets, these are typical villages in Indian eastern plain but are not as poor as the tribal lands in the mountains and forests of Orissa. The results of this study, to my knowledge, can be safely

Figure 4-1 Location of the JABA village in eastern coastal state of Orissa in India

generalized to most plain areas of eastern India with a high concentration of rural population at more than 150 million. The objective was initially to implement small renewable energy projects based on small hydro, SPV, or biogas in order to observe how modern renewable electricity could compete with the existing grid. As these villages were electrified around 1975, I could compare the decades old grid with my private entrepreneurial efforts to provide off-grid SPV lights. If the SPV or other renewables could be commercial and successful in an already electrified village, the SPVs should also be successful in the large markets of India’s remaining 20% yet to be electrified villages. As the demography, lifestyle, level of income and fraction of electrification (30-40% of the village households) were very similar to highly populated villages in the eastern coastal plain geographical region of India, I limited my intensive renewable energy project implementation to JABA village. Though only 104 households were selected, they constitute a very wide diversity of income, education, land endowment, social caste grouping, and household sizes. Further this size of the sample household, while being reasonable for statistical inferences, also helped us to limit the financial commitment and the capital investment within my limited annual budget of about $2,000, which later increased to more than $5000 by 2005 and $10,000 in 2008 from voluntary contributions and many fund raising events in India and the USA. The renewable energy implementation in JABA village is very broad (comprising biogas, SPV and some solar heating) and covers numerous end uses of cooking, lighting, running electronics for this thesis. I will focus here on applications of off-grid SPV and the rural grid.

4.3 JABA Village Description

This section contains the data collection and observation in JABA village in Orissa at the community, household, and individual levels. The reason for the selection of SPV is discussed along with the initial mixed result of success and failure of the private supply of SPV lighting. Electricity and kerosene use and income data collected from the door-to-door survey of 98 households in December 2003 will be used in my demand estimates in Chapter 5. The JABA village sample was selected from the geographical region as shown below in the Wikimapia Google Earth pictures (in Figure 4-3 and 4-4) within the polygon.

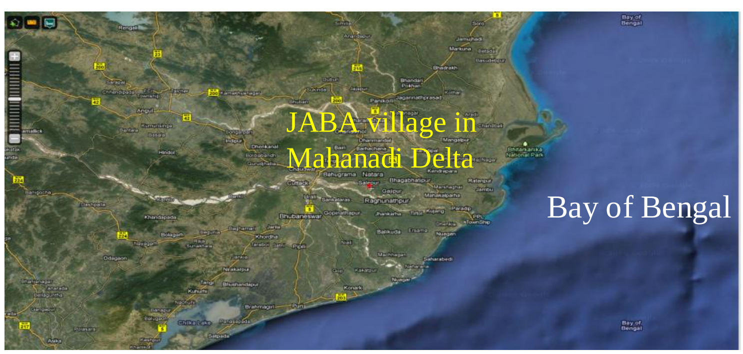

Figure 4-2 JABA village in the Mahanadi river delta of Orissa's Katak district

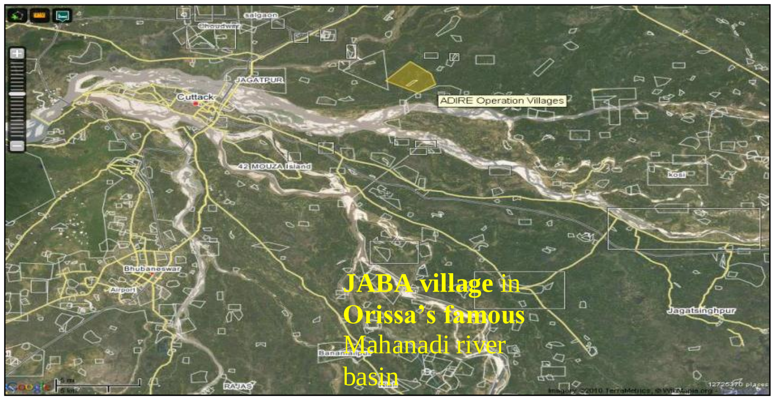

Figure 4-3 JABA operation villages are in the middle of plain land of Mahanadi delta

Please note the rows of the green tree lined hamlets in between the network of rivers. This is the famous Mahandi Delta close to the East Coast, Bay of Bengal and one of the most fertile and culturally advanced lands in the state of Orissa. The larger polygon below in Figure 4-4 shows the area where the off-grid renewable projects are implemented and from which the data were collected. The small brown patches in between the green tree-lines in the Google map (Figure 4-5) below are the housing settlements, and the large patches of plain lands are used for agriculture on which the villagers produce mostly rice, pulses, and other grains. Vegetables are produced in small parcels of land surrounding the homes.

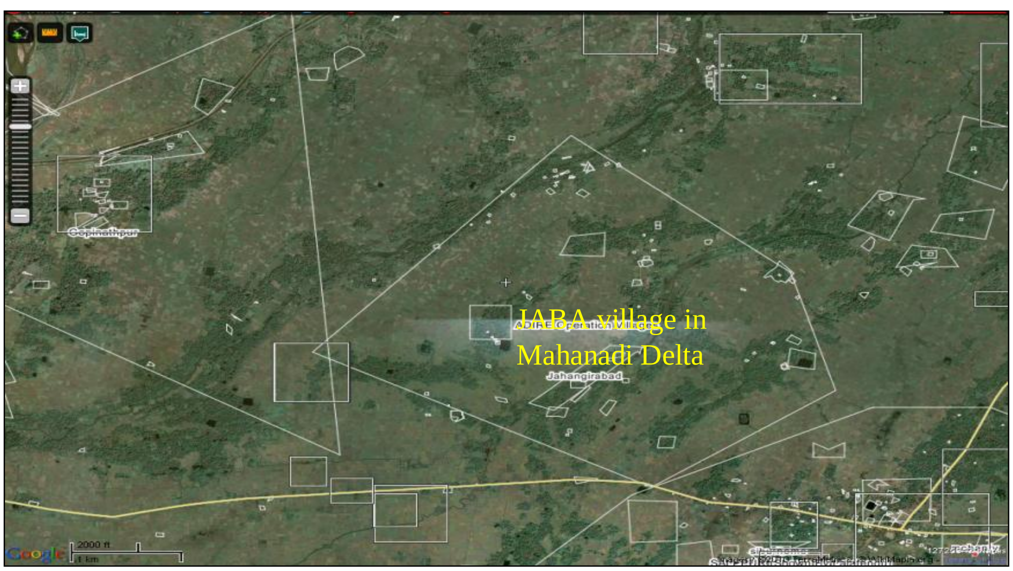

Figure 4-4 Closer view of the area surrounding JABA village

Figure 4-5 JABA village on one side of the small stream Kundi
Source: Wikimapia. 2010. (www.wikimapia.org search words: ADIRE, Katak)

The data collected are from individuals, households, and for the community.

Individual data: At the individual level, the JABA project team (later christened a non-profit trust named ADIRE) founded by me and led by my 80 year old father, collected the age, sex, education, health condition, needs and expectations of each family member. This allowed us to design our energy system to be of maximum value to the villagers and to prioritize their stated or perceived needs. If electricity is not the essential need at the moment for many individuals, the demand can be quite low. The electric blackouts, low voltage at the distant end of the line, and shorted electrical circuits are so normal that the villagers keep kerosene lamps in standby at all times.

Household level: We collected detailed house types (mud or brick wall; straw, concrete or tin roof), number of rooms, if it contain a bathroom, number of toilets, how much land, how many cows, and other assets that were easily identified from visual observation and face-to-face interview. The number of appliances and electrical devices were also noted during the interviews. The kerosene consumption reported by the villagers is typically their monthly controlled allocation by the government except for a few rich people who report more than their allocation. For grid using households, electricity use was estimated from their monthly bills. In many cases, the bills were not available and I used their recalled average monthly payments, prevailing electricity rates, or the number and wattage of electricity devices to compute the average kWh. However, many electrified villagers also did not know or had never even heard of a kWh. The kerosene and electricity data along with income data were used for the demand estimation.

Community data: Initially the agricultural, forest, grazing land, types, and number of trees, river water flow, and solar radiation data were collected by experienced villagers in very qualitative terms. It was easily noticeable that except for an un-electrified school building of four rooms, there was no other public building for any community gathering. The road was not suitable for motor vehicles and the flooding of river water, when it rained, kept villagers two miles from the local shopping center and paved road. Thus, a normal rain or storm brought the community to a standstill.

4.4 Data Gathering and Analysis

Primary household and community data were gathered with the help of five locally hired staff members in the village based on a detailed questionnaire emailed before the survey was conducted in summer of 2003. The project and data collection was supervised through the internet and ultimately verified in each of our annual field visits from 2003 onwards. This village is partly electrified; had a few rich but otherwise mostly poor households. All poor people are mostly illiterate, but there are a very few highly educated professors and engineers who live outside the village and send money to their parents. Like any caste-based society in Indian villages, I found all four castes in the village with the two upper classes richer and the two lower classes poorer. These classes also follow the same order of their social statuses as presented below with their locally known sub caste in the parenthesis.

Brahmin- teachers and worshippers,

Kshyatriya- administrators, farmers and accountant (sub caste: Chasa)

Vaisyhya- business(sub caste: Behera), *and*

Harijjana- labor providers (sub castes Bauri, Samal, Sethy) also called *Constitutional Scheduled Caste (SC*) with special legal status designed to bring them out of social and economic backwardness. They benefit from affirmative action programs in higher education and government jobs. All four castes live in perfect amity in this village of 104 households in JABA village. The Bauri and Sethy communities live in the electrified hamlet of the village but the Samal community is about 200 yards away from the nearest electric pole. There has been no demand for the grid supply from the Samal community. In 2009, they were told they would get electricity access through the subsidized program but at the completion of my thesis, nothing has been done.

The economic, skill, and education capabilities of the households in each class are equally diverse across these castes as can be seen from Table 4-1. Many upper class families are also poor because population growth lowered their per capita land holdings and they may have a lower skill level, making them unsuitable for any productive job. They are also hesitant to do pure labor and seek opportunities through government grants.

The closest city Kataka is about 25 miles from this village, but when the project started the village was still isolated from the nearby road from lack of the last mile of connectivity through a bridge.

4.4.1 Preliminary data analysis

The initial primary data illustrates mostly very low income with inequity of income and electrification of this caste-based society. The summary data below in Figure 4-1shows the poor state of the village. Like any other average village in Orissa, land ownership is less than 2 acres per farming households. The lack of sanitation is shown by the fact that only 30% of households have toilets. A clean drinking water supply could only be provided through ten hand pumps at the start of this research project. The new biogas digester, solar lanterns, and LED lights are also recent additions from 2003 of the village experiment arising out of this research.

Table 4-1 The state of JABA village: demography, income and some recent energy transition

Description	**Numbers**	**% of Total**	**Note**
Total Population	417		Total households 104
Farm Earners	87	21%	Total 135 acres
Cash Earners	48	12%	Jobs/Business
Toilets	30	7%	
Water Pump	10	2%	
Households (HH) Income/Energy use	**Number of HHs**	**% of households**	
Poor	100	96%	(Income <$200/m)
Rich	4	4%	(Income > $100/m)
Energy in households			
Wood/Dung	100	96%	Non-commercial 80 Kg/month
Kerosene	100	96%	Subsidized 3 liters/month
Electricity	40	38%	Subsidized from 1970s
LPG	6	6%	Subsidized from 1995
Biogas	10	10%	Unsubsidized from 2003
Solar Lantern	22	5%	5 homes with students subsidized shops Unsubsidized from 2003
LEDs	20	20%	Unsubsidized from 2005

Out of 104 households, only forty families had a grid electricity connection when we started the survey with average connection growth of less than two per year after 25 years of electrification. The village was first electrified in the mid-1970s. The rest of the households could not or were not interested because of unaffordably high costs related to the initial electricity connection, house wiring, and appliances needed to benefit from electricity. Figure 4-6 shows the acres of land in the family and the number of rooms in the house for the different castes. The land endowment and housing size of the upper three classes are much higher than the SC households. The focus of my initial research was on these SC households comprising 40% of the population with no electricity, education, or non-labor income. The SC group has significantly less agricultural land with only labor as a source of income

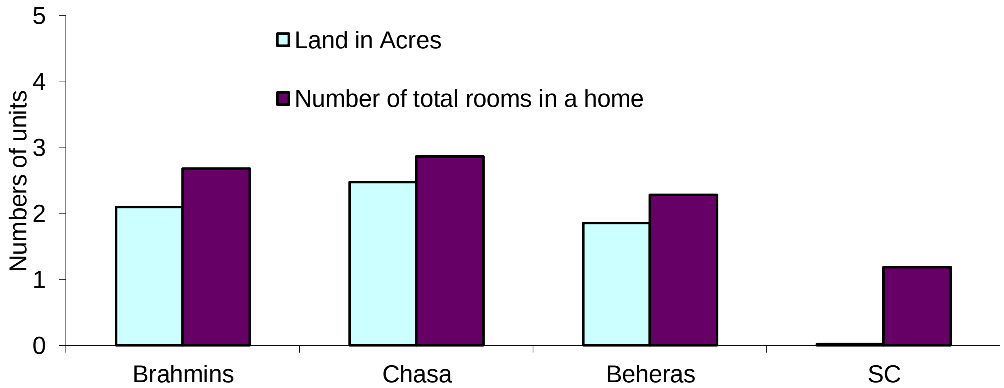

Figure 4-6 The land and resources of the stratified village

From figure 4-7, it is clear that most households have no concrete roofs, which is considered not only a matter of prestige and social status but also a safety issue during the frequent storms that often hit Orissa's coast. Even the upper classes have no toilets in their house, though they have electricity. Most households have one or two rooms, so the amount of electricity to light these homes is small.

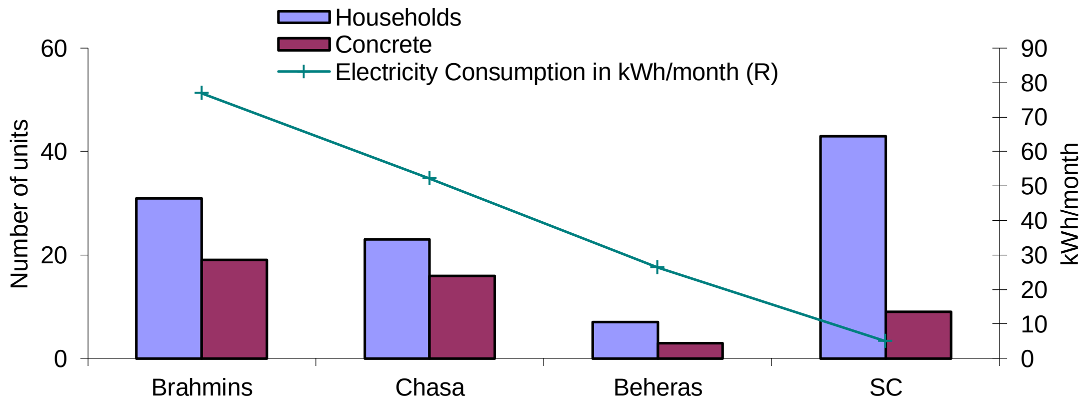

Figure 4-7 Housing and electricity consumption of the stratified JABA village

This encouraged us to try solar lantern and LED based solutions as well as to set up community facilities where a cluster of houses could try the solar-powered lights, TVs, and fans. These services could be supplied to households with a monthly fee to make the electricity service subsidy-free.

4.4.2 Income, expenditure budgets and spending profile

Table 4-1 shows the correlation between the high penetration of electricity and the economic and educational achievement across these castes: the higher classes are on the left and the lowest backward group with little education is on the right in Table 4-2.

Table 4-2 Household data (monthly average) 1 $ = 43.5 Rs. (Indian Rs)

	Social Groups	**Brahmin**	**Chasa**	**Behera**	**Harijan(SC)**
A	**Occupation & Education**				
1	Major Occupation	Service, Farming, Worship, landlord	Service, Farming, Petty contract / politics	Cow herds, farming	Washing, lease farming, land less labor
2	Highest Education	PhD/ Graduate	College	High School	High School
3	Majority Adult Level Education	High School	High School	Elementary	Elementary
B	**Demography**				
1	Number of Households	33	22	7	42
2	Total Members	152	90	37	138
C	**Sources of Income**				
1	Cash Income from **(Rs./month)**	3826	3695	3629	1450
2	Crop Income from Farm **(Rs./month)**	1591	995	1157	0
D	**Mandatory Expense**				
1	Food Exp. @ 10 Rs./day/head	1636	1227	1586	1000
2	Disposable Income after Food per month	3780	3464	3200	450
3	% Household with less food than minimum	0%	0%	0%	7%
E	**Energy Use**				
1	House % electrified	76%	55%	29%	5%
2	Number of rooms in a house	4	3	2	1
3	Electricity kWh/month	99	100	93	60
4	Electric heater Y/N	9%	0%	0%	0%
5	LPG access (Numbers)	5	1	0	0
6	Kerosene in liters	4	2	2	3
7	Fuel wood in Kgs	97	87	87	80
8	Fuel Expense Rs.	175	118	111	113
9	Electricity Expenses per electrified household Rs.	128.4	122.8	112.5	75
10	Electricity +Fuel Expenses Rs.	269	185	144	113
11	As % of Disposable Income	7%	5%	5%	23%

Source: JABA Case Study, 2009 Data collected in 2003

From the village survey, I estimated that a daily food expense of about Rs.10 per capita is required for minimum nutrition. With this level of food expense, I found about three SC families that did not have enough food to eat. The majority of the SC families and even many upper class families are undernourished due to malnutrition, unhygienic cooking practices, or eating stale food. The lack of proper storage facilities for the cooked food and the poor quality of the houses also adds to food contamination. The households also suffer from many water borne diseases, which are curable at a low cost through proper sanitation and clean drinking water. Neither a poorly funded government nor the villagers themselves (with their low education and cultural practices) have implemented these low cost efforts. The cost of numerous festivals, rituals, and family rites are considered indispensable compared to discretionary health and education spending. Regarding health related spending, our data showed that around 80% of the villagers had never been to a hospital nor had they consulted a doctor for years.

The relevance of such economic conditions is that villagers have many unmet needs and are badly in need of developmental aid besides just clean energy and electricity. Thus extending the grid, as has been the case for years, will not lead to the automatic increase in subsidy free demand for electricity. The energy expenses for lighting, electricity, and cooking have to be balanced with expenses for other daily necessities including food, drinking water, health, and education many of which have non-electric inputs. The doctors, medicines, teachers, electrical devices, and comfortable houses are all required to attract and retain these skilled people. Thus, social and economic development is also essential for SPVs or the grid electricity to be used productively and to be paid for. Electricity demand for such impoverished villages can be very small to begin with and can be easily supplied effectively through SPVs.

An electricity grid, which is important for large scale production, delivery and electrification of a rich home, has no use in such poor homes and communities with few appliances and cannot be paid for and will remain unviable. But SPV electricity on a small-scale could be viable because the monthly payment will be low. Light and small ICET devices such as a small TV and a cell phone can be easily and affordably powered from the sun and stored in rechargeable batteries to be used just when and in the quantity required. SPV supply, being modular, can suit the electricity budget of the poor, which is no more than $2-5 per month. The SPV delivers value to the community when complementary inputs such as a health center and schools exist that have appliances, lighting fixtures, or even computers to be used by skilled people. If health centers and schools need electricity, they can buy SPV electricity or rent it as and when they need it. Extending an electric grid at a huge cost, as in the RGGVY plan, to a school boundary without a budget for a school building, wiring, electrical devices and teachers and teaching aids will not be subsidy free and is economically wasteful.

Sources of Income: The data in Table 4-3 to 4-5 explain the basic economic activities and the factor incomes in JABA village. As the skill is only based on manual and primitive labor, the income for most villagers is at the subsistence level. These levels of skill, income, and socio-economic development do not show that village electrification has played any significant impact on modernizing or improving the productive potential of the villagers. Some income comes from government jobs or contracts, but most villagers are still farmers, farm laborers, or religious workers with minimal subsistence income.

Table 4-3 Income sources and activities in JABA village in 2003

Factors	Households own	Available units	Average Factors/HH	Income per month	Total village income per month	Household Income per per month
Skill	20	30 people	1.50	$ 100.00	$ 3,000	150.00
Labor	95	200 people	2.11	$ 25.00	$ 5,000	52.63
Farm Land	58	136 acres	2.34	$ 40.00	$ 5,440	93.79
Housing Land	104	50 acres	0.48	$ 10.00	$ 500	4.81
Waste Land	Com-munity	25 acres	0.24	NA	NA	NA

Table 4-4 Occupation in JABA village in 2003

Breakdown of the village activities	Population	Fraction %
1. Daily chores household	94	23%
2. Farm earners cultivation seasonal job	87	21%
3. Cash earners productive year round in government supported work	48	12%
4. Children unproductive	75	18%
5. Men idle unproductive	96	23%
6. Sick	15	4%
Total	415	100%
Breakdown of the 12% or 48 year round productive workers as (3) above		
Small Business	13	3.2%
Service in government jobs/funded projects	9	2.2%
Driving	6	1.5%
Mechanic	5	1.2%
Religious workers	5	1.2%
Medicine store	3	0.7%
Carpenter	2	0.5%
Computer (live outside the village)	2	0.5%
Mason	2	0.5%
Contractor	1	0.2%
Total	48	12.0%

Table 4-5 JABA village household electricity use and incomes

Group Name	Primary Income Sources	Fuel Sources	Number of households	Consumption kWh/month (Q)	Price c/kWh (P)	Income /month (Y)
Electrified Poor	Labor	Electricity	32	70	3	55
Non-electrified Poor	Labor	Kerosene	58	1	90	53
Electrified not so Poor	Skill, Capital, Land	Electricity	8	200	3	240

Source: JABA case study, 2009

4.5 JABA Village Energy Data Analysis

Table 4-6 shows the energy consumption in JABA village compared to all of India, Eastern India, and Orissa. There is less firewood use in the village. The average electricity use is relatively high, possibly because the village has been electrified for a much longer period than the average households/villages in the comparison.

Household energy spending and willingness to pay:

Residential energy spending is dependent on the household size, type of house, residents' activities, weather conditions, culture, income, price of energy, and the actual availability of the energy resources. Only four households have adequate income to regularly consume their 2 liter monthly quota of heavily subsidized kerosene available at $0.50 or 30% of the market price. It is a valuable fuel for lighting and cooking as a cheaper and much more predictable alternative to grid electricity. Only two families had installed cow dung based biogas plants costing about $60 under a matching government subsidy program. Many others still use cow dung as cooking fuel with all its negative effects on the health of women and children. Only two houses of the lowest socio economically deprived 42 SC households have electricity for lighting. All others do not have the land to keep cows or grow biomass for cooking fuel. They spend a considerable amount of time daily gathering biomass and often consuming unhealthy food in the absence of adequate fuel. The next forty relatively well-off households that have electricity, struggle to regularly pay their roughly two-dollar monthly electricity bill, which is heavily subsidized from the local utility. Sixty households still do not have electricity after decades of electrification and 3 years after the launch of the high profile RGGVY program in the country.

Table 4-6 Comparisons of JABA village energy consumption with that in India, Eastern India and Orissa

Sl No	Item		JABA	Orissa	East Coast Plain	India
1	Firewood	Kg/capita/day	0.69	2.10	1.19	1.22
2	Cow dung	Kg/capita/day	0.29	0.43	0.52	0.4
3	Agricultural residue	Kg/capita/day	0.65	0.65	0.73	0.47
4	Kerosene	liters/household/day	0.09		0.12	0.13
5	Electricity	kWh/all household/day	1.50		0.43	0.54

Source: Estimated from Dutta et al. 1997; Pohekar et al. 2005; MNRE 2009; and JABA case study

The electricity deprivation of the SC communities is shown in Figure 4-8. The two SC communities belong to economically and socially weaker sections of the society and have no electricity connection as shown in the right categories. Of about 100 resident families (4 families are non-residents) needing electricity service, 60 very poor families with incomes less than $50/month, still did not have the subsidized electricity by 2008. These families use inefficient kerosene lamps due to very low subsidized kerosene costs, which are not available to SPV devices. The rate of growth of the grid electrification of the village was less than 2% per year considering only about 30 households connected in 2003 and only about 40 households connected in 2008.This slow connection rate is despite the promises of the RGGVY in 2005 to connect all these poor houses to the grid. A recent survey showed that many poor homes in the un-electrified SC cluster have been provided electric wiring for about a year now, with a grid line yet to come near their homes.

The upper class families with a greater desire for reading and writing aspire to get an electricity connection. The villagers do not use many expensive electrical appliances as could be seen from Table 4-7. Only one house uses room heating and a washing machine, two houses have water heaters; four houses have refrigerators and eight households use water pumping in the absence of any piped water supply. After damage to the color TV from extreme voltage variations, one family spent around $100 for a stabilizer but could not afford to repair the TV. Therefore, it is clear to me that there is hardly any consumer paying capacity or willingness to pay for the government grid electricity that is being planned for these communities.

Only an affordable and reliable source of energy will be sustainable. Even a small quantity is acceptable, if they can pay only a little now and consume more as their income grows and the technology proves reliable and becomes acceptable.

Most of the villagers were living in mud and thatched houses with very little cash expense to maintain until the 2000 super cyclone damaged their houses. After the cyclone in 2000, the government gave grants for building one roomed houses, but still only 30% of the houses have a concrete roof.[11]

This research, therefore, tried to assess how small the demand is for electricity, and why many families do not even care to acquire electricity services. An initial observation in the village showed very low demand for energy and electric lighting in most of the homes. This result matches with the recently released study in villages in Utter Pradesh (MNRE, 2009).

Even in electrified homes, the types of appliances used were not very efficient when we started the survey. Fluorescent tube lights were used by only 35% of electrified homes. However, in a later survey, we found that many electrified homes switched to fluorescent lamps with the efficiency awareness spread through this project, reduced costs of lamps, and the one-year warranty provided by the suppliers.

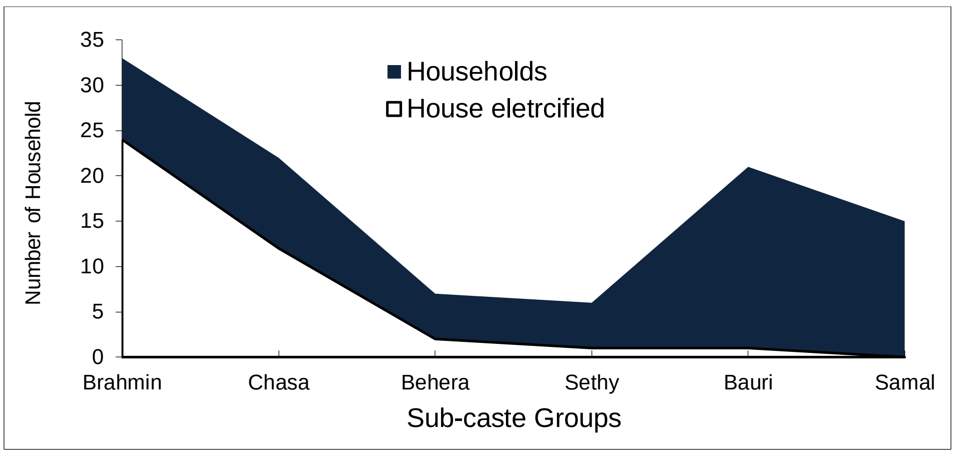

Figure 4-8 Electrification in JABA village by numbers in each caste group (2003)

Table 4-7 Number and types of appliances in 2003 used by the electrified households

	Bulbs	Fan	TV	Tube-light	Water Pump	Refrigerator	Water heater	Washer/ Drier
Total numbers	184	78	32	17	8	4	2	1
HHs have	40	32	32	14	8	4	2	1
HHs do not have	64	72	72	90	96	100	102	103
% HH don't have	62%	69%	69%	87%	92%	96%	98%	99%

[11] Inadequate household income evidently works against any credit offer for housing from the commercial banks that led to the government decision to provide grant. The same credit issue also explains why there is no market for consumer finance in rural areas from the electricity appliances to the grid connection costs or modern SPV devices. As a government grant is limited in a developing country with low tax base, it is essential to target such grant and subsidies wisely to reduce the future costs and increase revenue. I thought that SPV devices could meet this objective very well. A one-time investment in solar light will reduce the cost of the electricity connection and perpetual subsidies for the electricity or kerosene costs. It might also increase the education and income of the villagers if they use the brighter, pollution-free, safe light during evening times instead of kerosene. Instead of a grant to households, it is felt that the SPV lights can be paid for by the households on a daily/weekly/monthly basis as is done for the kerosene.

The picture below shows the energy using assets of one middle class home with an income above $200/month. They are still using the primitive wick lamps shown in between two kerosene hurricane lanterns. Also shown are a kerosene container bottle with a blue funnel on the top and a camphor-fuming device (extreme right behind the wood pole and on the right of a big rice storage silo) for repelling mosquitoes in an electrified home.

Figure 4-9 Kerosene lanterns in a grid electrified home

The data that we collected also showed us various important unmet needs of the villagers. Water, toilets, roads, and a hospital were most needed by the villagers as inferred from the survey results shown in Table 4-8 below. When we estimated the budget to meet these very basic needs, the energy budget was only about 10% of the total.

Table 4-8 What the villagers need the most-Not Energy ($1= Approx. 45 Rs).

Important Basic Needs	Number of people wanted	Quantity Planned	Budget in Rs.
Toilet	210	42	50,000
Road	186	2 Km	50,000
Bridge	101	200 meters	200,000
Hospital	66	2 beds	50,000
Water Pump	53	5 KW	50,000
Water	47	10 Hand pumps	50,000
Energy	12	20 solar lights	70,000 (11%)
Park/Library	1	1 building	10,000
Temple	15		100,000
Total Initial Investment Plan in 2003			630,000

Only 12 people showed an interest in some form of energy for light or cooking fuel. Even after villagers were told about the solar lights and shown the solar lantern in action in the village-park, during road construction, and for farm production activities, the interest of the poor remained lukewarm as the cost was perceived to be high, and to make this affordable a small micro loan would be necessary. Unless the very poor are provided modern education, health, services and production tools, they do not see the need for electricity and are not willing to pay for it. When they are not willing to pay for the low cost SPV, it is hard to imagine how they will pay for the higher cost grid power. This might explain the very low growth of the grid connection, less than 2% per year, and the continuing need for high subsidies for the uneconomic rural grid. This low growth is a commercial problem for the grid business as grid supply and investment cannot be controlled in small lots to meet the current needs of the rural poor. However, the SPV based lighting, ICET, can be exactly matched with the poor's demand level, and the capacity factor of such devices would be higher than that of the grid. The government provision of solar lights to 100% of the electrified villagers in the state of Haryana for study also shows the poor value of the grid for education. This could be equally applicable to this Orissa village. I inferred from this case study that starting with small portable SPV based lighting, phone, and TV and then graduating to higher electricity loads for pumps, fans, and transportation will avoid such redundant investments in both the grid and the SPV in Indian villages. This will drive economical and ecologically sustainable development without the worry of global warming and local pollution. Such a phased implementation will be subsidy free and encourage efficiency that has not been possible in the rural grid business.

Electricity, the most expensive subsidized fuel in rural India, is mostly used by the rich villagers, while kerosene is used by the poor. (See Table 4-9 for energy subsidies in JABA village.) The rich households get about $12/month of grid electricity subsidies at 90% of the cost as can be observed from Table 4-9. This important information can indicate the barriers that government subsidies can create to adopt new technologies. While looking for a comparison of the true average costs of the grid with the SPV systems, I could not get any publicly available data from the Indian utilities but could roughly impute the grid costs based on the literature (Owen, 2004; Miller, 2003) of at least 30 cents/kWh This led me to consider introducing the SPV to compete with grid as an individual entrepreneur. All poor and rich villagers including my family members are not convinced that I can make the argument that SPV is cheaper than grid when the SPV upfront cost is so high and grid upfront cost is negligible and the monthly costs villagers pay are about $2 as shown in the table. It is also difficult to convince villagers to pay the true costs of SPV as they do not appreciate that they get about 90% subsidies in the grid supply because it is not mentioned anywhere in the bill or newspaper. However, they still complain that grid power is unaffordable compared to their income. To spend 2-4% of income only on electricity when the food and milk share is 90% of the remaining costs is not a small matter for them (Bose and Shukla, 2001). This is an initial problem of any commercial venture around an SPV system in Indian villages. The more the grid is subsidized, the more will be the need to subsidize SPVs to enter the rural market.

Table 4-9 What is subsidized the most? Grid electricity!

Source	Quantity / month	units	Market Price $/unit	Market Cost $/month	Subsidized Price $/unit	Subsidized Cost $/month	% Income spent	% subsidies
Electricity	70	kWh	0.30	14	0.03	2.10	2-4%	90%
Biomass	80	Kg	0.30	24	0.30	2.40	2%	0%
Cow Manure	50	Kg	0.00	5	0.00	0.00	0%	0%
Kerosene	3	Liters	0.80	2	0.25	0.66	1%	70%

4.6 JABA Village Renewable Energy Feasibility

Various renewable energy resources such as biomass, hydro, wind, biogas, and solar in the village can be considered. I will show that SPV even at its current high price could be the best option with the lower village consumption and skill levels in the face of adequate solar resource endowment in the village. I will also show that though they cannot be developed immediately due to lack of skill and awareness, the other available renewable technologies can be usefully applied in the village and will be cheaper than the grid. I have deferred the implementation of these projects in the village but will take them up later if the SPV prices do not fall significantly in the next 5-10 years, and/or if the village demand for electricity increases to a high level where SPV cannot meet those needs. After 7 years of observation, I see that neither the villager's skill nor demand have increased significantly enough to explore the mini-grid solutions. Before I discuss the opportunities and issues of the solar project in this case study, I briefly review the village energy resources that prompted us to select SPV.

4.6.1 Energy endowment and technology selection (state Orissa and JABA village)

Biomass: The state of Orissa is full of agricultural and forest lands; agriculture taking up a very high percentage of the geographical area in all the districts. Rice is a big part of the cultivated crops. Rice husks are normally used as cattle feed, and rice straw bales are often used as thatch for poor houses. After a year of use as shelter, they are further used as organic decomposition in an open pit. Both rice husks and straw are very useful for biomass energy applications. In addition, there are special kinds of wood, which can be transformed into biomass power that are available in the forests of Orissa, but not close to JABA village. Due to current alternative uses of the existing biomass resources, the cost of transportation for distant wood, and the complexity involved in setting up a biomass power plant and getting the skills to run them, we did not consider biomass an option for the village.

Micro Hydro: In JABA village, there is a small water stream called Kundi River. It has water only during the monsoon and is almost dry during all other seasons. The river is extremely dependent on rain and canal water and, located in a plain area, may require a large reservoir in this populous terrain. It would be very expensive to have a minimum water head for a conventional micro hydro plant. The river water, during the rainy season, as a dam or a dyke will not create any usable water head due to the excessive flooding. Thus, a micro hydro project was immediately abandoned. But a waste area of about 25 acres in the river bank on one side of JABA provides good opportunities to harness solar and biomass energy for export to nearby villages or future local consumption.

Small Wind: The availability of another important energy resource, *wind,* is low in JABA village. Wind maps of India indicate no good wind potential in this location. The capital and skill required to set up, operate, and maintain a wind plant is also difficult to find here.

Thus, with no cheap land, capital, skill, and water resources available for biomass, small hydro and wind power projects, they were dropped. So now, we are left with two more viable rural energy resources. The first is cow manure for the production of biogas (a gaseous mixture of methane and CO using the anaerobic digesting process) popularized by the Indian government for heating and cooking applications; this is practical in almost 40% of Indian rural households with 3-4 cows. The second is modern solar electricity using SPV technology that was yet to be popular in rural or urban applications, when we started this project.

Biogas: The biogas energy sources in JABA are about 167-200 cattle with an average of two cattle per household. Cattle dung is widely used as a dried fuel cake for cooking. Women, besides their other daily chores, normally prepare this cheap but dirty fuel when they have no other productive jobs. The biogas program to convert this useful organic matter to both energy and fertilizers is very large in India. JABA got this technology only in the last 5 years with our effort. It is possible to convert biogas to electricity through cheap gasoline generators to back up SPV electricity, but we do not find that necessary at the current level of village demand. This is a valuable energy source for electrical energy at a price lower than SPV for village production centers. However, it lacks the portability, modularity, safety, and low operating and maintenance benefits of the SPV, which is more useful to power small electrical and ICET devices of the poor households in the village. In order to provide a large amount of clean heating energy and reduce the need for household solar electricity, biogas projects were implemented in JABA. This, however, helped only the relatively richer households with enough cows, land and access to water and cheap unused labor. Most of these households also have access to the highly subsidized grid electricity. Further, the use of biogas for cooking by the richer households can hinder the economies of scale electricity grid. Thus having chosen SPV, I will turn to SPV resource endowments in the village.

SPV electricity: SPV was selected for domestic lighting due to year-round availability of solar energy in JABA village, and the access to enough land area to generate solar electricity from private rooftops and backyards without requiring land acquisition or the complex organization to manage a hydro or biogas project. I will describe the more recent solar endowment data now available for Orissa from a study by Diederichs (2009) as the local information was not available at the start of the project. We depended on a NASA study, which is not very different from the data we have now. The following data will show the minimum and maximum solar endowments that can be used as the range of solar insolation available in the village.

Solar Resources of Orissa: In the entire state of Orissa, the air temperature varies through the year from 17 °C to 32 °C and the ground temperature varies from 18 °C to 36 °C. The annual mean temperature is amongst the highest on earth, with an annual average of about 28 °C. The most important factor is the "Insolation incident on a horizontal surface". Its annual average values are between 4.68 kilowatt hours per square meter per day (kWh/m2/day) and 5.00 kWh/m2/day. The daylight hours do not vary very much throughout Orissa, with a maximum in June/July and clear skies most of the time except the rainy season. The clear sky days vary from an annual average of six to nine days with the clearest sky during the month of December. Another important factor is the insolation clearness index **K**. This factor is calculated by the insolation on a horizontal surface over the insolation on top of the atmosphere. In all of Orissa the annual average values vary from 0.50 to 0.54 and the monthly average values from 0.31 to 0.64. This variation is also due to the changing of seasons. The high amount of clouds during the rainy season prevents the sunrays from reaching the ground. The daytime cloud amount all over Orissa follows a graph formed as a bell with a minimum in the month of December (between 18 % - 30 % of clouds) and a maximum during the wet season in the month of August (80 % - 90 %).

Image 1: Graph with highest and lowest districts values for monthly average insolation incident. [kWh/m2/day]

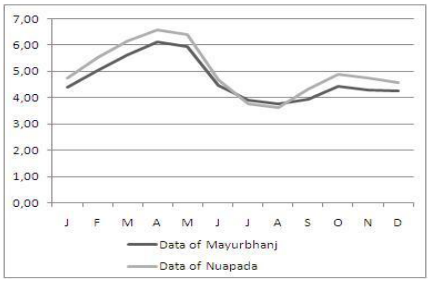

Image 2: Graph with highest and lowest districts values for monthly average insolation clearness index K.

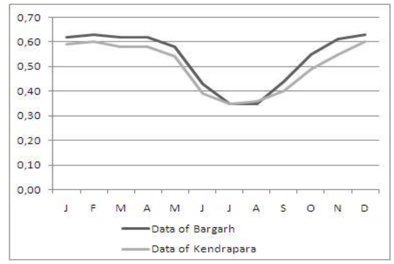

Image 3: Graph with highest and lowest districts values for monthly average clear sky days. [days]

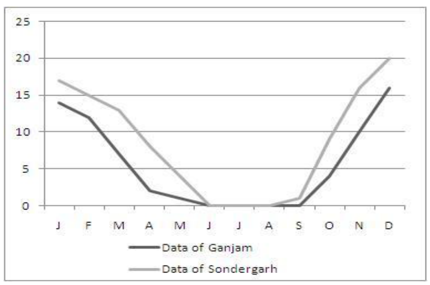

Image 4: Graph with highest and lowest districts values for monthly average daylight hours. [h]

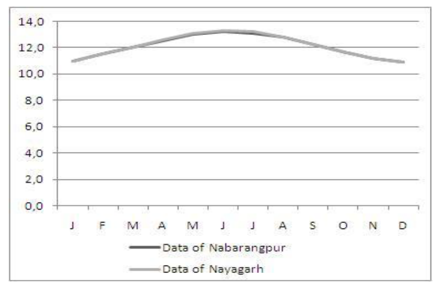

Figure 4-10 Endowment of Solar energy in Orissa
Source: Report of Opportunity - August, 2009 Nicolas Martin Diederichs

In the JABA village, one of the primary local energy resources is solar energy, which is available throughout the year except during 2-3 monsoon months on the Indian east coast. These rainy days are not too bad for solar systems unless the clouds cover the sky continuously for 3-4 days. Mostly the continuous cloudy days are limited to only a few days of the week in August-September. The river, “Kundi” on one side of the JABA village has good potential through the in-stream hydrokinetic machines, which are being developed to produce electricity without requiring a dam. This will help in the rainy season when the river stream has plenty of high speed, high volume water flowing to complement the lower solar supply. The possibilities of running low head turbines with a pumped storage facility with water stored through solar pumping during the daytime may be feasible in the future to avoid evening battery storage for other productive uses during the intermittencies caused by cloudy days. In the future, biogas and biomass can also supplement SPV electricity if the price of SPV does not fall rapidly. I believe that by the time the village skill and demand is sufficiently high in the next 5-10 years, the SPV price would have fallen by half. In that period, if electricity use is significantly higher than it is today, the SPV would require supplements during cloudy and night hours of operation from any of the other renewable resources discussed above. The micro-grid or hybrid power generation in the community could help meet the need for light in community streets, buildings, and production centers. It is also possible that instead of the lead acid batteries that are being used now, more powerful but clean and safe lithium phosphate batteries will be available to store solar energy for portable applications including for electric vehicles and bikes.

4.6.2 **Solar lanterns introduced at individual family level**

Though both lighting through SPV and cooking through biogas were implemented, the focus here is on SPV. Even in the grid electrified homes, the hidden costs of the grid electricity are high due to the need for a backup battery and kerosene lanterns. The rural lifestyle and production activities require portable lighting and ICET devices. These additional considerations plus the appearance of compact fluorescent emergency lanterns in the local market by the turn of this century persuaded me that SPV would be more useful for numerous portable applications. A solar lantern which is a sturdy rechargeable lantern powered by the SPV panel of 7-10 Watt was first introduced in 2004 and subsequently expanded in 2005. All products and services were procured from the open market without any subsidies and often paying the value added taxes.

With the objective of providing basic energy needs of the rural people through renewables in a cost effective and environmentally friendly manner, I started by addressing the basic lighting needs in 2004 through various financial mechanisms, including my own investment, and donations from friends and relatives. I donated one solar lantern to the village temple, another to a family with school going children and installed one solar system in my home in the village, which also worked as the project control room for the initial 3 years. My larger home system runs computers, fans and a battery charger for other hand tools and gadgets. It also served demonstration purposes. Twenty more solar lanterns were given to poor families with school going female children in 2005.

In order to lessen the burden of household work, such as collecting and cleaning kerosene lamps, and encouraging girls to go to school, priority was given to those families with school going girls. Solar lanterns were introduced at around Rs.3500 ($80) per lantern and were given to people through a micro financing credit loan. One solar lantern, on a normal sunny day, provides light for 4-5 hours when charged fully during the day. People had the flexibility to pay back in monthly installments of $1.5 for five years, either in cash or through labor that might be required by the research project for any village developmental work. The monthly installment was calculated based on the existing average monthly spending per household for subsidized kerosene lamps. It also recovers my initial investment reducing the subsidies burden.

Figure 4-11 Demonstrating solar and LED lanterns

These portable solar lanterns provide night light for various purposes including home study, a health camp shops, community events, etc. as can be seen from the pictures below on the left. Besides being portable, solar lanterns increase productivity because they provide reliable power anytime anywhere in contrast to the Indian Government's welfare program for the poor providing one incandescent lamp to each family in the village (shown below at the right side). The same amount of light can be delivered through a much safer and more productive LED/CFL lamp powered from battery SPV systems without subsidies for value-added activities requiring portability, reliability, and flexibility for multiple uses.

SPV systems given to individuals and shops were monitored regularly. Two local electricians were trained in solar electricity systems and a micro finance team was entrusted to organize the rental business, train users to maintain a good credit rating, and make productive use of the lanterns so that we recover the full cost of the solar lanterns. The plan was to use the collected money for the monthly salary of the solar electrician and for purchasing more solar lanterns. Initially we planned to rigorously enforce collection and payment discipline. However, the transaction costs to collect less than one dollar a month became so high that we thought of waiving the initial costs of small systems for the first time. Later, however, we redeployed the high cost solar lanterns by renting to shop owners who saw more value in reliable light and adopted smaller LED lamps at less than $40 for poor homes. We could waive the upfront costs of

LED lamps and distributed a few of these lights without solar panels free. Many high school children got excited to build their own LED lamps with support of the solar technicians and the battery recharging stations we had built. This will make anyone wonder how the electric grid company with its government bureaucratic structure can do a successful business in rural India where they collect only $1-5/month of total revenue per household that is not more than $200 /month even if all 100 households are grid electrified. This in all likelihood will not recover the costs of the billing, collection, and customer management costs leaving aside the expensive on-peak electricity costs and the huge sunk capacity costs of the distribution assets. The centrally planned and government owned/regulated grid operators have no capacity, ability, and knowledge or motivation to take up these small scale but valuable projects.

Figure 4-12 Contrasting multi-purpose SPV portable light with the rigidly fixed grid electricity light in rural application for poor

Source: JABA CASE STUDY, left panel and RGGVY, MOP website photo on the right: the grid connection cost is about $500 plus a current economic costs of 18 cents/kWh*100*6 /1000 kWh/day = 10 cents/day against the portable solar lantern cost of $80 and no recurring costs.

Solar lighting system introduced at community level: Besides the solar lanterns, with an outside donation, one solar lighting system supporting two lights and one fan was installed in the local primary school, which had been running without electricity. Solar home lighting systems

(SHS) are larger capacity solar systems of 40W with a 40AH (Ampere hour) battery tailored for a small household to provide 3-4 hours of light for two 13W CFLs with the possibility of using a 12V DC fan or a low watt TV. It can also be used as emergency backup power for the rural grid. Using these solar lights, evening reinforcement classes were conducted for free for the village children who needed after school advice or tutoring. This solar system is not as portable for day-to-day outdoor use as a solar lantern and costs about $300, which is clearly unaffordable for most families in the village. This home lighting system is, however, found to be very convenient as backup grid support as an uninterrupted power supply (UPS) for running fans, computers and some domestic appliances that do not require a lot of energy. The project work in the village used this system for reliable solar power for community gatherings, health camps, and water pumping as the grid supplies blackout for hours and days at times without any notice. The performance of the solar systems was closely monitored and two local youth were trained in solar light maintenance.

Figure 4-13 Roadwork at nights using solar lantern to avoid the scorching heat in summer
Source: JABA case study, Orissa being close to the tropics, summer nights are not as short as northern latitude countries. Therefore, farm and street lights are required for longer hours and will have more value.

Solar Photovoltaic and LED based programs: SPV based lighting and entertainment created additional labor time at night and encouraged human resource development through learning and better health. Harsh Indian summers are known to affect labor productivity. In the summer, solar energy is plentiful and is being captured through SPV panels in solar portable lanterns and radio for use at night. The workers relax during the summer heat in their home with solar operated fans and work on the farm during the cooler night. The lights are also used for outdoor work, sewing, weaving and other income related endeavors. Solar powered lights and LED lights have also given lots of income generating opportunities by renting them out during public festivals, weddings and other private ceremonies in nearby villages.

Collections of service fees for solar lanterns were regular when the local electricity was disconnecting a large number of customers for nonpayment of electricity dues. As soon as the subsidized grid supplies were restored with lax enforcement by a government managed grid operator, collection of dues for solar lights were drastically reduced.

4.6.3 **Observation of a phased development plan**

It would have been easy to provide SPV electricity to all 60 un-electrified households at less than $10,000 but the lack of road, bridge, school, transport vehicle and health facilities would not have helped villagers even with electricity. Further, it would have been much cheaper to use the supply of heavily subsidized grid electricity than the off-grid SPV that I introduced (Grid subsidies are over 90% though later I prove the grid is more expensive than SPV) but no transformation in rural, health, education, lifestyle, and production would have been seen without reliable electricity and a supporting infrastructure. Therefore proposed began to phase in electricity in addition to other supporting services. I introduced small solar lightning ICET systems to build local skill and infrastructure from the large unused cheap labor force of the village. This possibility of doing things in phases and the impossibility of doing everything in the village with the help of villagers also helped me wait for the SPV price to come down through international efforts in research and development. In spite of my best effort, the skill set of the villagers has not come to a level where they can use a large amount of electricity such as for running an electric car or refrigeration plant. Thus, the demand for electricity still remains low to power a few lights and small water pumps. Only recently we have a plan to produce organic food by irrigating a few acres of land during the dry season and are planning to buy a 1kW solar water pump at a cost which is 50% below the cost five years ago.

Local suppliers for computers, laptops, projector, cameras, and printers being technology intensive have very poor service support in the village. The internet is the only source for online help from our camp office in the U.S.A. We provide maintenance for these technologically advanced products and for solar panels for health equipment like nebulizers and oxygen masks. Broadband internet would have helped us deliver these services more efficiently, but is still not available in this village. The existing dial-up internet connection is too congested to transmit educational photos and videos from Google, Wikipedia, PBS kids.org, and others. While we felt the lack of this infrastructure is a handicap for village development, a similar handicap was not felt for lack of or insufficiency of grid electricity as the SPV electricity was adequate for the current needs

Figure 4-14 Solar power removes rural darkness and drudgery

Source: JABA Case study: Picture starting in upper left and going clock wise are:1. A traditional kerosene lantern converted to an LED lantern by our village technician at the cost of $10, 2. Solar powered fan, light, TV, water pump available in local market. 3. Solar LED lights being used during festival, 4.Safe 12V DC solar CFL lamp closer to the idol being worshipped 5. Small $5 LED based lighting more safe, weatherproof, and portable for rural mobility 6. Comparison of the small LED light indicated in 5 with a wick lamp.

Figure 4-15 Solar water pumping during building construction which require either manual or very low 40-100W efficient DC pump

Source: JABA case study (2005-2009)

Solar powered street lights expanded for community safety and productivity: Four solar powered street lights were installed by local solar technician in JABA village streets. The light posts were built by local resources with locally produced compressed earth blocks. A solar powered community center meets Health, Education, Lifestyle support and Production (HELP) needs.

Figure 4-16 Solar lights installed by a local technician on village streets, solar street light near the BioCafe in a formerly pitch dark unsafe street corner

Adividya Mandir, a new school in JABA to provide modern education to the socially deprived, is now fully powered by SPV for lighting, fan, laptop charging, projector, water pumping, and regular health camps. High powered LEDs have been used in the health center building and village café. The solar energy center equipped with LED and battery-charging devices regularly provides battery charging and maintenance services to the villagers and streetlights, school students, and amenities of the Adividya School and ADIRE staff. The off-grid solar powered health center and school is shown in Figure 4-17.

Figure 4-17 SPVs to power an energy efficient off-grid building with classrooms equipped with laptops, lights, fans, projectors, and LEDs for day and night activities, which also works as the health, adult learning and entertainment center

Now we have enough background information and data from this typical Indian village to calculate the costs of SPV and the grid as well as demand functions for villagers of various income groups and finally to calculate if SPV and electricity subsidies are, in fact, required. We will also use these derived functions to analyze if a subsidy free rural grid supply is possible by 2020. Table 4-8 summarizes the energy use and income data of the JABA village from which 98 usable data points out of 104 total households were collected and processed for cost, price, and demand analysis. Some of the relevant grid and kerosene energy and income data will be further analyzed in chapter 5 with more implications of the study to follow in Chapter 6.

4.7 Summary of the Case Study

The electrified JABA village in Orissa, selected for this data and field experience, enlightens us about the cultural, economic and financial issues involved in supplying grid and modern SPV electricity to rural households in India. The incomes of the villager households were found to be below $100/month. The electricity consumption was limited to 60% of households with consumption mostly limited to lighting fans and TV. The large amount of biomass and cow manure used for cooking reduces the need for electricity. The electricity needs were not found significant enough to justify the electricity grid. A few 40 W solar home light systems that can power a middle class village home is adequate to meet the basic health, education, and production needs in community building and shops. The unreliable grid alone could not have met these needs without SPV support.

Though the deployment of SPV for domestic and community application was technically successful, there remain significant information barriers as to the true cost and demand, anti-competitive grid pricing, and lack of a skill-base to create a big demand for any form of electricity unless highly subsidized. In the next chapter, I will provide the economic theory for the cost comparisons, demand and supply curve estimation, and their dynamic interactions with the support from the literature. The consumption data of kerosene, grid, the cost and demand for electricity for the basic needs of the villagers as collected in this case study will be used to complete the empirical analysis for answering whether off-grid SPV is cheaper and subsidy free now and in the next 10 years compared to the grid. I will show methods to fund the off-grid SPV programs in Chapter 6 by removing the existing grid inefficiencies as discussed in the literature review.

Table 4-10 Basic statistical summary of JABA village demography, energy and incomes

	Population	*Age*	*Land*	*Rooms*	*Kerosene*	*Fuel-wood*	*Cattle*	*Milking Cow*	*Cow dung*	*Monthly Cash Income*	*Farm income*	*Food*	*After-Food Net Income*	*Electricity spending*	*Fuel Expense*	*Elec+Fuel*
	Nos.	**Years**	***Acres***	***Nos.***	***Liters***	***Kg***	**Nos.**		***Kg***	***Indian Rs/Month***						
Household Count	104	104	102	103	97	99	99	99	73	101	104	104	104	99	99	104
Sum	417	3622	135	215	283	8165	167	45	2505	285050	74100	125100	234050	4720	12520	17240
Mean	4.01	34.83	1.32	2.09	2.92	82.47	1.69	0.45	34.32	2822	712.50	1202.88	2250	47.68	126.46	165.77
Standard Error	0.23	0.87	0.15	0.15	0.12	3.65	0.15	0.07	2.26	264	88.70	67.54	275	6.42	5.70	10.32
Median	4	34	1	2	3	80	2	0	30	2000	300	1200	1300	0	110	135
Mode	3	34	0	1	3	80	0	0	30	2000	0	900	2000	0	110	110
Standard Deviation	2.30	8.87	1.50	1.57	1.20	36.35	1.50	0.66	19.28	2651	904.54	688.81	2800	63.86	56.68	105.26
Sample Variance	5.27	78.76	2.26	2.47	1	1322	2	0	372	7028424	818192	474458	7839878	4078	3213	11081
Kurtosis	9.67	0.00	1.58	6.93	11.99	2.70	2.05	1.60	4.48	7.95	4.35	9.67	6.84	4.56	3.96	4.73
Skewness	2.33	0.25	1.19	2.04	2.57	0.53	1.00	1.37	1.46	2.39	1.64	2.33	2.16	1.71	1.97	1.60
Range	16	44	7	10	9	200	8	3	120	16700	5100	4800	18200	350	280	670
Minimum	1	17.5	0	0	1	0	0	0	0	300	0	300	-1200	0	40	0
Maximum	17	61.5	7	10	10	200	8	3	120	17000	5100	5100	17000	350	320	670
Largest(3)	10	52	5	6	6	200	5	2	75	10000	2700	3000	8000	220	310	416
Smallest(2)	1	18	0	0	1	0	0	0	0	300	0	300	-1100	0	50	0
Confidence Level95%	0.45	1.73	0.30	0.31	0.24	7.25	0.30	0.13	4.50	523.36	175.91	133.96	544.53	12.74	11.31	20.47

5 CHAPTER -5

THE RESEARCH QUESTIONS

I have acquired cost and electricity consumption information in Chapter 2 and Chapter 4. I have the data for estimating demand from Chapter 4 to answer the four research questions as follows.

Q1. Cost Analysis: Is off-grid SPV electricity cheaper than grid electricity for the rural poor in India?

Q2. Demand Analysis: Can off-grid SPV electricity or grid electricity be subsidy free for the rural poor in India?

Q3. Threshold Income Analysis: What are the break-even incomes for the grid to be cheaper than off-grid SPVs?

Q4. Dynamic Dominant Firm Equilibrium Analysis: Can this break-even income and consumption be reached for the electricity grid to be competitive or subsidy free by 2020?

Answers to Q1 to Q3 require the computation of the curves in Figure 5 which were developed in Chapter 2 and 3 and repeated here for easy references. Each curve is labeled with its corresponding question and a table defining the equations follows the figure. The answer to Q4 will require a dynamic analysis of the static equilibrium shown in Figure 5 with the use of the appropriate price escalators in a time dimension.

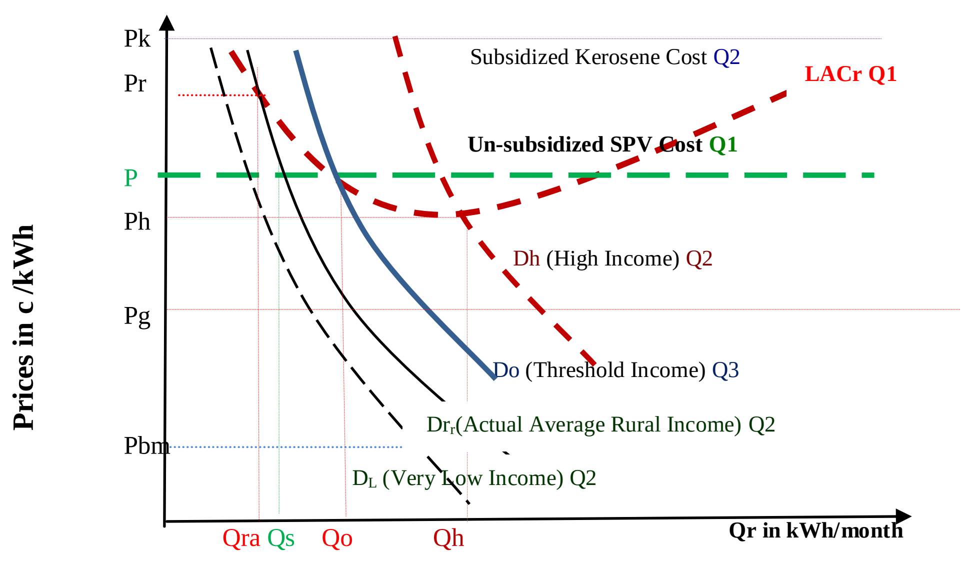

Figure 5 Equilibrium conditions of SPVs and grid for poor homes at various demands D(P, Y)

Note: Q1, Q2, Q3 indicates the questions where these functions will be estimated

Figure 5 above shows a grid electricity market with supply costs and demand curves in rural India in competition with kerosene and SPVs as substitutes. Table 5 below summarizes for the reader most of the variables and the functions that will be estimated in this paper.

Table 5 Variables and equations in Figure-5 to be estimated and determined

Questions on			**Variables**	**Description**
Q1	Supply Curves	1	LACr	Long-run average cost of the rural grid electricity
		2	Ps	Average cost of solar photovoltaic electricity is the same as the SPV market price
		3	Qs	SPV equilibrium consumers demand
		4	Pg	Marginal/average energy cost of grid electricity
Q2	High Demand Price and Output	5	Dh	High income (Yh) demand function
		6	Qh	High Income grid electricity consumption in kWh
		7	Ph	High Income grid electricity price in c/kWh
	Low Income Rural Grid Output	8	Dr	Actual average rural income (Yr) demand function
		9	Qr	Average rural electricity consumption in kWh
		10	Pr	Average income rural market clearing price
	Very Low Income Demand	11	D_L	Very low income consumers demand function
		12	Q_l, P_L	Very low income consumers price and consumption indeterminate
	Kerosene Supply	13	Pk	Cost of kerosene lighting in c/kWh
Q3	Threshold Demand Price and Output	14	Do	Threshold income (Yo) demand function where grid starts becoming cheaper and subsidy free
		15	Qo	Threshold consumption level (Qo at Yo)

In Q1, I will estimate the long run average cost of the grid (LACr), marginal variable cost of the grid (Pg), and marginal cost of SPVs (Ps) and compare the effective costs of the conventional, monopolistic grid with the emerging, modular, and competitive SPVs in rural India. Q1 will address the high average cost of the electric grid due to the high peak period loads, high losses, longer lines, lower capacity utilizations, and lesser load density characterizing rurality. The costs of the SPV technology is in no way negatively affected by this rurality. It is rather helped by more land and the self-servicing by surplus labor that reduces the already low operating expenses of the SPVs. The role of energy efficiency to reduce the average cost of SPV electricity will also be presented in this section 5.1.

Then I will proceed to **Q2**, which deals with poverty, another familiar characteristic of rural India where the average household income was less than $100 in 2009 and is not likely to grow more than 10% in this decade. In Q2, I will estimate the demand curves at various levels of income. At the very low income (Y_L), households have a demand function (D_L) that is too far below the cost curve (LACr) to create a viable subsidy free market-clearing price. At the somewhat higher rural income (Yr), the rural demand function (Dr) is in equilibrium with the grid LACr, but the grid price Pr, at the market clearing consumption level Qr, is higher than the SPV price Ps depending on the slopes and shapes of the cost and demand curves. Only with a high-level income such as Yo or Yh with the demand function at Do or Dh, can a subsidy-free grid market be created. The optimal condition of lower price Ph and higher quantity Qh compared to the SPV price Ps and quantity Qs respectively are achievable only under high income markets. The challenge is to find whether the rural demand for electricity is D_L, Dr, Do, or Dh. I will show quantitatively in Q2 that the current grid demand level in rural India is low at D_L or at a maximum of Dr because of widespread rural poverty. The lack of modularity of grid supply necessitates a subsidy regime for the grid market to clear in such poverty prone rural areas. Such demand analyses at the household level will be presented in section 5.2. As the demand for the village community and small production programs do not need much more electricity than households demand, no separate demand study is required for the non-household sector.[12] When income is high enough for a grid demand of D_o, the grid is just beginning to be subsidy free and has a market-clearing price that is the same or less than that of the SPVs. I will designate this income as the threshold income (Yo), which will be estimated in **Q3** of section 5.3. At the threshold income (Yo) as shown above, the demand function (Do) results in the quantity demanded Qo where the grid price converges with demand price Pe. Mathematically, the threshold condition for a subsidy free grid is Pe = Pr = LACr. When the subsidy free grid price is less than Ps, the grid is clearly the cheapest option and is dominant in the rural market.

Q4 will use the equilibrium solutions of the supply and demand curves in Figure 5 and the dominant firm model discussed in Chapter 4. They will be projected to 2020 to observe whether demand will reach Do or beyond and be high enough for the grid to no longer need subsidies and to be cheaper than SPVs. The use of the learning curve effect and the residual demand curve will be used in this section 5.4.

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[12] Large farmer's demand is also not considered in this analysis as only a handful of farmers in a typical village in Orissa use grid electricity. They also depend on expensive diesel fuel, which is also subsidized. These customers contribute just 1-2 c/kWh, which does not recover even a small fraction of the marginal energy costs. Even if the grid technology can provide electricity service during the off-peak period, the infrastructure to separately extend such lines, schedule, monitor, meter, and bill the consumption will be much higher than their willingness to pay. In effect they do not add to the true demand for grid electricity. SPV and biomass power could be a better alternative, but that will be another study for the future.

As discussed in the thesis, both the rural grid and the SPV supply do not assure reliable power during the peak periods. Thus, the assumption of the equal quality of service for both SPVs and the grid will be used in this study in Q1 to Q4. The need for battery support is equal in both the rural grid and the SPV environment, and to that extent, this assumption will not be as strong as it might appear at first. I will show that this assumption is very valid in my case study where the intermittency problems will be solved for SPV systems more elegantly than for the grid by supplementing them with the customers' own battery reserves and the judicious choice of energy efficient portable appliances and devices.

The possibility that off-grid SPVs can provide subsidy-free rural electricity, which in turn increases the urban grid efficiency, will provide the foundation to break off the urban grid from the rural energy supply. I will also show this as an implication of the analyses of this chapter in section 5.5.

5.1 Q1- Is the Grid Cheaper Than Off-grid SPV Electricity?

Answer: *To supply electricity requires equipment or capacity and the electrical energy flowing through the equipment. The costs depend on these two variables. There must be enough equipment or reserve to meet the peak load capacity of Qc kW and the actual electrical energy use of Qr kWh/month. Considering the low consumption level in rural India and the high cost of supply, I will show that grid electricity is not cheaper than SPV electricity below 20 kWh/month electricity of use at ½ kW peak load capacity or below 40 kWh/month electricity of use at a 1 kW peak load capacity.*

A review of the urban grid network with lower electricity cost has already been provided in the literature review. Since rural distributors buy power from the wholesale grid mostly during peak periods, I will begin by calculating the rural grid peak power costs and show after the efficiency adjustment this is very high.

The related questions in Q1 to be answered:

I will now compute the average costs of the grid and SPV electricity in order to prove that the grid is not cheaper than the SPV option in rural India. While answering the above question, I will also address the following three related questions,

a. What is the average cost of grid and SPV electricity at the 1 kWh/day/household (30kWh/month) household consumption targeted by the Indian government RGGVY plan?
b. If there is one at all, what is the break-even level kWh electricity consumption when SPV average cost equals grid average costs?

c. How does energy efficiency affect the monthly cash outlay and the average costs of the grid vis-à-vis SPV electricity?

Assumptions:

Some of the cost and demand data to answer this question are derived from the RGGVY plan and from other government agencies involved in the promotion and regulation of electricity in India.

1. The 35% rural distribution loss factor is calculated in the literature review and assumed for this computation for delivery of energy and capacity. I will split this total distribution loss into 8% for the primary high voltage (HV) losses from the wholesale market and 27% for the secondary low voltage (LV) distribution losses.
2. Marginal cost of the energy component of the rural electricity service is computed based on wholesale market prices during peak periods. The marginal distribution cost of rural electricity is the average cost of the new distribution facilities owned by the utility and the customers and their O&M costs. These marginal costs represent the true opportunity costs of the next unit of production. As distribution plants are lumpy and cannot be added in small kWh increments, I will calculate these marginal distribution costs as the incremental average cost of the new assets ADCr. The marginal loss adjusted energy costs from the competitive wholesale grid Pg as well as the average SPV costs are calculated from market data and assuming these markets are in perfect competition average costs are equal to the marginal costs.
3. Modi (2005) and NRECA (2007) have argued the investment cost per rural customer in the Indian condition will be about $500. I will also calculate the investment cost per kW of customer's peak load using the feasible number of household electrifications in the JABA village in Orissa, where we implemented the SPV electrification and compare it to this RGGVY investment cost.
4. All calculations in this question are based on an inflation rate of 5% and all discounting is done on a nominal 14% cost of capital close to what has been considered by the Central Electricity Regulatory Commission (CERC 2009;2010)
5. Useful Life n.

   For Grid n=25 years

   For SPV n= 25 years for all outdoor modern thin film and crystalline PV and 10 years for dye sensitized-organic indoor flexible panels used for appliance charging.
6. The cost of grid power depends on two variables--reserve capacity for meeting the peak capacity of Qc kW of a customer and actual electricity use of Qr kWh/month. The fixed upfront investments and annual costs are calculated on a per customer basis with a base case

assumed peak load (Qc) of 1 kW. A linear rate of capacity charge has been applied for a higher (2 kW) and a lower (1/2 kW) peak capacity. The minimum capacity of ½ kW has been chosen since the poor will use only a few incandescent bulbs or CFL/TV/Cell phones within this ½ kW load.

Assumptions and formula used for the levelized cost of energy

Levelizing upfront costs to annual and monthly levels requires financial assumptions and the discount factor. The financial assumptions for the calculation of the annual levelized costs are summarized below.

Weighted Cost of Capital

Debt (D) 12% and Equity (E) 16% at 50:50 D:E; Composite cost of capital i =14%

Range of discount factors for sensitivity testing i = 0% -16%

Tax Rate 0%

The capital recovery factor $CRF = \dfrac{(1+i)^n * i}{(1+i)^n - 1}$

At 14% discount factor and 25 years SPV/grid CRF= $1.14^{25}*0.14/(1.14^{25}-1)$ = 14.5%

At 14% discount factor and 10 years SPV life CRF= $1.14^{10}*0.14/(1.14^{10}-1)$ = 19.2%

O&M Expenses

5% of capital costs and inflated at general inflation of 5% for grid power leading to a levelized O&M cost factor ORFr of 7%

0.5% for SPV investment costs inflated in the similar manner as in the grid leading to a levelized O&M cost factor ORFsof 0.66%

*Annual Levelized Fixed Cost = Investment Cost*CRF + Annual Levelized O&M Cost*

As shown in Figure 5-1, the U shaped curve is the long run average cost curve LACr of the rural grid, which will be computed in Step1 below. LACr is the sum of the grid average variable costs Pg and the average distribution fixed cost ADCr:

LACr = Pg+ ADCr. (5-1)

Pg is the average variable grid cost for lighting, TV along with information, communication, entertainment, and education technology (ICET) loads, which will be determined from the wholesale market price, Pw, with adjustments for electrical losses in Step 1-1. The average distribution cost ADCr will be computed in Step 1-2. ADCr is the average distribution cost for supplying 30 kWh/month electricity to a poor household. ADCr can also be called the average capacity cost when the grid is being expanded to meet the poor customer's electricity needs. This will be calculated in steps 1-2, starting from the specific distribution grid investment per household (DI). LACr is the sum of Pg and ADCr, which will be shown in steps 1-3. The supply curve of the unsubsidized SPVs is shown as cost (Ps) and will be calculated in step 2. In step 3, I will show that LACr is higher than Ps under the prevailing rural conditions of low consumption and more so when modern efficient devices are considered. Step 4 will be the conclusion of Q1.

Table 5-1 provides the summary of the important functions and variables that will be estimated in this question. While describing the computational steps in this question we will come across many intermediate variables. They are summarized in Table 5-6 at the end of the first step.

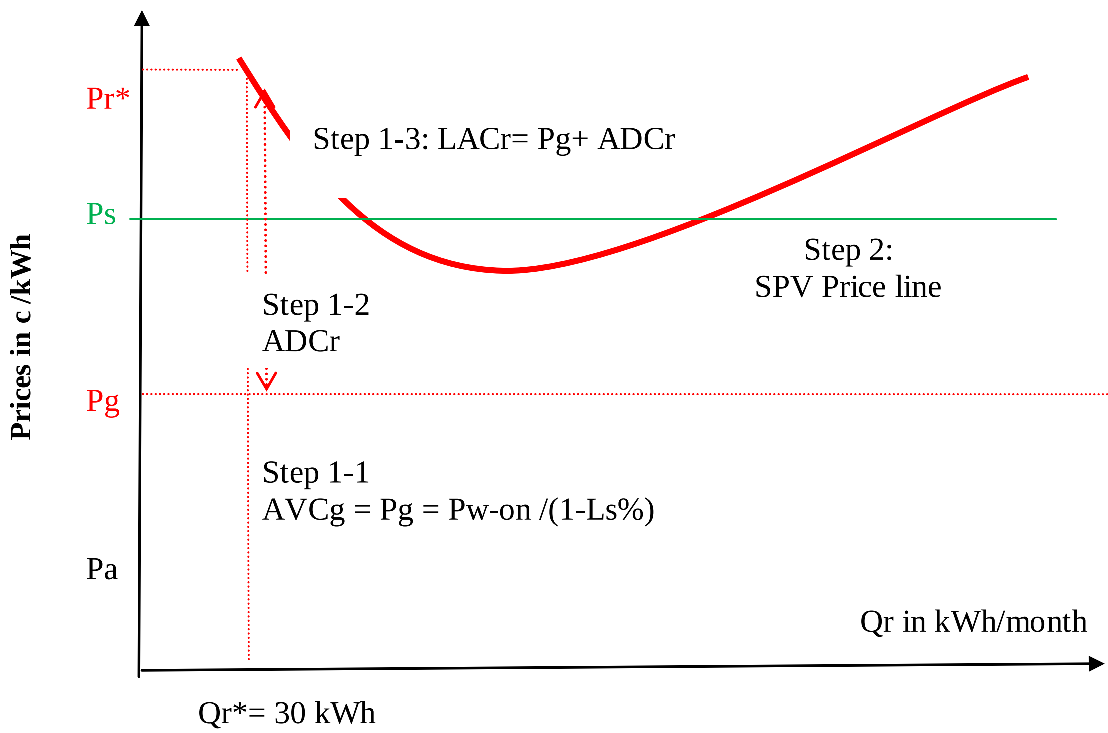

Figure 5-1 Equilibrium of SPV and grid for poor homes: Computational steps with targeted consumption Q_r*= 30 kWh/month/household

Table 5-1 The definitions of variables and functions used in computation of LACr

		Variables	**Governing Equations**	**Description**
Supply Cost of Grid	1	LACr	AVCr+ AFCr = Pg + ADCr	Average cost of grid electricity LACr is the AVCr plus the average fixed cost AFCr, capacity Qc kW at the specific capacity cost of Pc in $/kW/month for actual electricity consumption of Qr
	2	Pg	(Pw-on) adjusted for the 35% efficiency loss	Pg =AVCr, average variable energy cost of rural grid adjusted for losses
	3	Qr*	30 kWh /month/household	Rural poor consumers' demand administratively fixed in India
SPV supply cost	4	Ps	Constant	Average cost of SPV electricity

5.1.1 Step 1: Determining components of LACr

This section will describe the average cost of the rural grid, which is the sum of the average cost of the energy procured from the wholesale market (Pg), and the average cost of the rural distribution system (ADCr) as described below. I will first describe the computational steps of the average energy cost (Pg) in Step 1-1 followed by steps 1-2 (a, b, and c) for the ADCr of the grid supply.

Step 1-1 Computation of Pg (Marginal/Average Cost of Grid Electricity)

There are two methods for calculating the marginal grid costs **(Pg)** at the wholesale level. One is the long-term, cost-based approach, starting with the fundamental engineering cost calculation. The other is the market based marginal cost of the wholesale electricity as available on an hourly basis in the short-term market.

Wholesale market based approach: I will adopt this newer and shorter market based method where all wholesale costs are avoidable and variable with the transparent price determination in the day ahead and real time markets. The detailed rationale and components of this wholesale market that will determine the marginal grid electricity costs are:

- The open access to the wholesale market simplifies the avoided marginal cost calculations by focusing only on the hourly energy costs of electricity in the wholesale market. All the generation capacity, fuel, and ancillary services are included in a single energy price in this market called the "Energy-Only" market. The new Indian power exchanges and the real time pricing for imbalance energy are also similar to the features of an Energy-Only market where the ancillary and capacity services are bid and cleared as parts of the energy prices in each period. These organized markets are fungible for all surplus economic generation capacity and energy, though they have not reached the maturity of the organized markets in developed countries.

- The total average costs of these generation and ancillary services in the wholesale market (Pw), available on an hourly or 15 minutes interval, can be calculated for two broad price periods: on-peak and off-peak. The on-peak energy is procured from the wholesale market at price (Pw-on) for meeting on-peak electricity needs such as evening lighting and entertainment, which are coincident with the power system peak. The off-peak energy price (Pw-off) is often used for powering agricultural water pumping and non-critical loads, which are very low in non-agricultural and poorly electrified villages and will not be considered here. The Pw-on prices will be estimated from the average prices of the previous year in the Indian wholesale market.

If Ls% is the loss from the wholesale market to the customer meter, total energy cost of selling Qr kWh of energy at the retail meter is given by calculating how much energy must be purchased from the wholesale market.

$$Qr = Qw\text{-}on\ (1\text{-}Ls\%) \qquad (5\text{-}2)$$

Equation 5-2 can be rearranged to get the wholesale power purchases in terms of retail deliveries,

$$Qw\text{-}on = Qr/(1\text{-}Ls\%) \qquad (5\text{-}3)$$

We know the total cost of purchasing Qw-on is Pw-on*Qw-on. Substituting this into Equation 5-3, we get the total variable cost of rural electricity in terms of delivered energy as

$$TVCr = Pw\text{-}on*Qr/(1\text{-}\ Ls\%) \qquad (5\text{-}4)$$

Let Pg = Pw-on/(1-Ls%), so Equation 5-4 can be written as

$$TVCr = Pw\text{-}on/(1\text{-}\ Ls\%)*Qr = Pg*Qr \qquad (5\text{-}5)$$

It is quite easy to see from Equation 5-5 that the true avoided energy cost of the rural grid is the on-peak wholesale energy price adjusted for the losses and is given by

$$Pg = Pw\text{-}on\ /(1\text{-}\ Ls\%) \qquad (5\text{-}6)$$

The supporting data for the computation of marginal energy costs from the prices available in the Indian wholesale markets is shown in Table 5-2. I have a number of wholesale prices to choose for Pw-on. Power is traded by independent power traders bilaterally, on power exchanges, and in local power pools. The all-hour wholesale market price through bilateral trades between utilities has been shown in the table as 15 c/kWh. The prices through the independent power traders are in the range of 15-18 c/kWh and depend on the time of day traded. The other prices are from two power exchanges (Indian Energy Exchange IEX (16 c/kWh) and Power Exchange of India limited PXIL (17c/kWh)) and two regional power pools (North-East-West

(NEW 12c/kWh) and South (16 c/kWh)), which are also indicated in the table.

I will use the Pw-on of 12 c/kWh in the NEW electricity dispatch region because it is where Orissa is situated. Also since it is the minimum price, it yields the most conservative or lowest average cost of grid power. The sales by the utilities through the regional load dispatch centers involve very little transaction costs. The opportunity cost of rural power after adjusting for the electrical efficiency losses of 35% as in Equation 5-6 is 12/(1-0.35) = 12*1.54= 18.12 c/kWh. I will round this to 18 c/kWh as a conservative estimate of the grid variable energy cost of rural electricity supply (Pg). The off-peak prices through power traders are also very high as shown in Table 2. However, these trades are not for the entire off-peak periods. They only occur sporadically during off-peak and may reflect the shortage of flexible generation and demand side resources.

Table 5-2 Summary of Indian electricity prices as traded in wholesale market Pw

Market energy prices in c/kWh		Utility Bilateral	Through Power Traders			Two Approved Power Exchanges		Pw-On in North-East-West (NEW) and South Regions	
Month	Source Period	All Hours	Peak	Off-Peak	Total	IEX	PXIL	NEW Region	Southern Region
Average in **c/kWh**	13 months July 2008-Aug 2009	15	18	15	16	16	17	12	16

Source: Central Electricity Regulatory Commission (CERC 2009) $**1= 45 Indian Rupees (Rs.)**

The highlighted average rate of 12 c/kWh will be used in my cost analysis of the rural grid as the input of the wholesale power cost.

Step 1-2 Average distribution cost of rural grid (ADCr)

Next, this purchased power must be distributed to rural customers. Unfortunately, there is no direct way of measuring the ADCr per customer from market data as the distribution investment is not fungible and cannot be sold in a secondary market. The up-front investment must first be determined. The local distribution utilities must pay for the capital (UC = utility capital costs) and O&M (OM = operation and maintenance) costs to distribute this power. The fixed distribution capital consists of long rural HV (high voltage) substations and primary feeder lines, LV (low voltage)) distribution transformers and secondary distribution lines. Additionally customer's must have their own investments and operation and maintenance expenses (CC = customer capital costs) for service lines, meters, house wirings, and domestic safety and protection systems. Then total distribution investment is DI = UC+ CC and the total distribution cost is DC = UC+ OM+CC.

I levelize the total distributions investment cost DI to monthly total costs (TDCr) using the capital recovery factor CRFr and O&M recovery factor ORFr for the rural grid as follows:

TDCr = (1/12) (CRF*UC+ ORFr*UC+CRF*CC +ORFr*CC) or

TDCr = 1/12(CRF*(UC+CC) +ORFr*(UC+CC) or

TDCr = 1/12(CRF*DI+ ORFr*DI) (5-7)

I include the non-fuel distribution O&M costs as part of the fixed costs because of the need to maintain and keep the power system electrically charged to avoid the theft of electrical parts and devices. If the distribution system is not kept charged, conductors and other assets will be stolen drastically reducing the assets value. Many such instances have been reported in Orissa distribution systems recently (OERC 2009).

Last, to get ADCr we need to allocate the total monthly costs over the kilowatt-hours consumed. The monthly distribution costs (TDCr) can be computed and billed to the customers either in terms of capacity (Qc) or in terms of energy use (Qr): TDCr is equal to the unit cost of capacity (Pc) times total capacity demanded (Qc) or the average cost of electricity consumed (ADCr) times the amount of electricity consumed (Qr) or

TDCr = Pc*Qc = ADCr*Qr. (5-8)

Where the units for these expressions are as follows:

(1) Pc is in terms of $/kW peak capacity

(2) Qc is in terms of instantaneous peak load kW (capacity demand) of customers

(3) ADCr is in terms of $/kWh of metered electricity distributed to the customer

(4) Qr is in terms of rural grid electricity in kWh/month

Solving Equation 5-8 shows that our average distribution costs are a function of both capacity (Qc) and energy use (Qr).

ADCr = Pc*Qc/Qr (5-9)

Since I need ADCr, I will first use Equation 5-6 to compute TDCr for a customer normalized to require 1 kW peak capacity to get Pc and then use Equation 5-8 to derive the ADCr curve as a function of Qc and Qr. From the observed and targeted values of the Qc and Qr in rural India, I will compute the values of ADCr.

Step 1-2 a. Computation of distribution investment per customer (DI)

The distribution system is lumpy and idiosyncratic. Upfront investment is required for capital that will last 25-30 years. If the customers do not utilize the massive distribution system, all assets will become stranded. Only through careful planning and allocation of the costs to a sufficient number of customers with adequate load can the distribution costs be recovered. Such recovery is easily done in the urban grid system. The distribution grid operators arrange reserve margins in the distribution system with sufficient spare capacities or through looped networks. They include redundancies in line and transformer capacities for the reconfigured loads. The RGGVY program, in particular, with its top-down government owned features and desire to achieve an ambitious deadline is not expected to have such a well thought out optimal distribution design. The future growth of consumers along with their income and consumption profiles are big unknowns. It is possible that the investment cost will be high and the amount and quality of the service will be low.

Nevertheless, I will use the new construction cost data for distribution facilities given under RGGVY to compute the average distribution costs. This is the benchmark cost that needs to be compared with the alternative SPV technologies. The calculation of the average distribution costs will include the average of the customer's own costs. The average connection costs are the market cost of customer installations that are also available from the RGGVY data.

The distribution investment related fixed costs DI = UC + CC: Total utility distribution investment costs (UC) are incurred for the physical distribution facilities to deliver the utility energy to the customer. In the Indian grid, the length of the primary feeder, which is of a medium voltage, is designated as MV. An MV is 3-6 kilometers long, serving 4-10 villages, each with a distribution transformer (DT) of 60-100 kilo-Volt-Ampere (kVA) capacity. The secondary low voltage lines (LV) emanating from distribution transformers are often 1 kilometer long, serving 40-100 small rural customers. I will distribute this total distribution investment to customers based on their reserved load or the contribution of their appliances to the distribution system peak during peak hours. Table 5-3 shows the calculation of the fixed upfront costs of the rural grid based on the RGGVY cost data of fixed investment for the grid distribution system. This utility investment cost per customer and the customer's own investment cost are the starting point of the fixed distribution cost calculation.

DI = UC+CC

The total grid upfront investment costs for electrifying a village in India was taken from the average village investment planed in the RGGVY program. The original 2005 estimate of $15, 555 investments per village had increased to $28,900 by 2008. For hilly and tribal regions, as in the state of Orissa, these estimates are as high as $40,000 per village. The reasons cited for the cost increase and slower electrification are the poor capability of contractors, lack of awareness of villagers to get connected, acquiring tax waivers and other bureaucratic delays, as well as land and forest clearance delays. Due to such wide variability of the costs of the village electrification, I want the minimum possible cost to electrify a village to assess if a village close to the grid can be competitive with the SPVs. Thus, I will take $15,555/village in 2005 as my conservative or low cost estimate of a village electrification cost. This is probably close to half of the current average village electrification costs. Based on my experience in the JABA villages, I assume a 40kW village level peak load for a village cost per kW of $15550/40 = $389.75/kW, which I round to $390 in the last column in Table 5-3.

The point to be noted here is that this computation is based on the average investments per village in normal terrain not very far from the main grid or for a village, which is already electrified, but needs reinforcement for about 40 kW customer peak-loads in a village of 100 households.

The $48 customer specific connection costs do not vary much across households. I use the market prices of the 2008 plan document, to compute the marginal connection cost. But I have added an additional $22 per kW of house wiring expenses including the minimum grounding and protection devices which a customer has to pay. The UC and CC from Table 5-3 are used in Equations 5-8 and 5-9 to compute TDCr and ADCr

Table 5-3 Estimate of the rural grid distribution fixed costs for a village

One 62 KVA distribution transformer in a village can serve 40 customers out of a total of 100 households. Average customer with normalized peak Load Qc = 1kW**; Exchange Rate: $1 = Rs. 45 (Indian Rupees)**				
Indian government estimate for RGGV rural electrification program				
Investment costs		**Overall utility cost $ per village of 40kWpeak**		**Customer Cost Per $/kW**
At the level of →		Utility (2005)	Utility (2008)	Customers cost 2008 data
Upfront capital costs (UC)			28,900 (for plain terrain) 40,000 (for hilly terrain)	Utility cost of villages closer to the central grid 2005
LV Distribution 1 Km	a	2,222		56
MV Distribution 3 Km	b	13,333		334
Upfront capital costs UC)	**1 (a+b)**	**15,555**		**390**
Connection costs (CC)				
House wiring(#)	c	-	-	22
Service wire and meters	d	-	-	48
Connection costs (CC)	**2 (c+d)**			**70**
Total capital investment DI = (UC+CC)	**1+2**			**460**

Source: RGGVY (MOP 2005; 2008) Though the house wiring cost is partly funded by the RGGVY for BPL families, these have no ground protection, as these families are not expected to run any appliances but only 1-2 light bulbs. But for our standard 1 kW load,

> I think grounding is essential and house wiring will be more elaborate than the simple circuit of the RGGVY plan.

Computation of TDCr and ADCr: There are costs for operating and maintaining the physical transmission, distribution, and generation facilities (O&M) and the administrative and general (A&G) costs required to run the electric utility. These two costs will be combined as a single annual cost for simplicity at 5% of the capital investment in distribution plants, which I will escalate at 5% per year. Like the grid investments, the escalating O&M costs need to be levelized to determine the annual costs that would be added to the levelized investment costs. On most occasions this O&M cost is expressed as a percent of the gross investment DI and added to CRF for the DI. The annual levelized cost of this fixed O&M will be about 7% of the initial capital investment (DI) and will be added to the annual fixed costs to calculate the total annual grid delivery costs. The total nominal levelizing factor will be 14.5% + 7% = 21.3% which is based on the nominal cost of capital and the escalating O&M charges. The computation steps for the annual capital recovery costs and the annual O&M costs have been shown in Table 5-4.

Taxes and transfers: The taxes the utility is required to pay and the public benefits the utility is required to provide are often passed on to the consumers, but this cost is a transfer payment, which is irrelevant for this study.

Computation of distribution capacity cost (Pc in $/kW/month): I will do a similar computation for 1/2 kW capacity (the lowest feasible level for grid electricity) and 2 kW capacity by prorating the above capital costs. The customer using less than ½ kW load will pay for ½ kW capacity and the customer using more than ½ kW but less than 1 kW will pay for 1kW capacity and any customer using more than 1 kW will pay additional capacity charges for each ½ kW increase in peak load. Table 5-4 shows these upfront costs for the three different maximum distribution system capacities. The investment per customer of 1 kW ($460) has been prorated for each of these Qc to show the average fixed cost of electricity per customer. The highlighted middle row uses as input the output data from the previous step, total investment cost per kW from line 3 of Table 5-4. I calculated the monthly costs by using levelizing factors for the capital and O&M costs. As can be seen from the last row of the calculation above, the average distribution cost per customer is $4.13/month for poorer homes for ½ kW loads, $8.26 for a 1 kW load, and $16.6 for richer homes that use more electricity and heavy power equipment up to 2 kW. For simplicity and to be on the conservative side and to not overstate grid costs for comparison with the levelized cost of SPVs, I will round these capacity costs down as shown by ≈ in the table.

Although these costs have not been computed by any utilities in India, I believe I am not overstating grid distribution costs as Wisconsin utilities (Wisconsin Electric Power Company 2008) reported distribution capacity costs significantly more than $8/month excluding meter and customer specific charges. They compute meter and customer specific charge of more than $20 /month in urban areas and over $30/month in rural areas. Such high monthly costs in the USA are due to superb customer services, rugged distribution investments, and quality of supply to customers often having loads as high as 5-10 kW because electric heating is more commonly used as natural gas is more expensive and not available in rural areas.

Table 5-4 also shows the ADCr for each Qc at the government targeted Qr* = 30 kWh of consumption by dividing the monthly costs Pc*Qc by Qe = 30 kWh.

Table 5-4 Cost of distribution capacity (Pc) at various levels of grid electricity usage (The middle column for the normalized capacity of 1 kW gives TDCr = Pc)

Maximum Connected Load or Capacity→	**Qc = 0.5 kW**	**Qc = 1 kW**	**Qc = 2 kW**
Limitation of appliance use→	Only a few 100W bulbs, a fan and TV can be used simultaneously No iron, heater or power equipment	Barely a heater or small power devices can work	Can use irrigation water pumps, power or most heating devices
Upfront Capital Investment DI=UC+CC	230	460	920
Economic Life in Years	25	25	25
Salvage value assumed to have negligible impact on 25 years assets	0%	0%	0%
Discount Rate	14.00%	14.00%	14.00%
CRF Capital Recovery Factor	14.5%	14.5%	14.5%
First year O&M (% of Investment)	5%	5%	5%
Escalation of O&M costs/Year	**5%**	**5%**	**5%**
ORFr Levelized annual O&M factor	**7%**	**7%**	**7%**
Levelized Fixed Costs in $/Year	33.34	66.68	133.36
Levelized O&M In $/Year	16.10	32.20	64.40
Total Levelized Cost $/Year	49.44	98.88	197.76
Calculation of the Monthly Costs, TDCr			
TFCr Levelized Fixed Capital Costs $/month	2.78	5.56	11.20
TOMr Levelized O&M $/month	**1.35**	**2.70**	**5.40**
TDCr Total levelized $/month **TDCr rounded $/month**	4.13 ≈ 4.00	8.26 Pc≈ 8.00	16.60 ≈ 16.00
ADCr Average distribution cost at 30 kWh	13.4	**26.7**	53.3

Next, I develop the ADCr functions for various levels of electricity consumption as = ADCr for

1/2 kW = 4/Qr

ADCr for 1 kW = 8/Qr

ADCr for 2 kW = 16/Qr

Rounding the capacity costs down to $4/kW for 1/2 kW, $8/kW for 1 kW, and $16 for 2 kW, the graphs of the functions are shown in Figure 5-2.

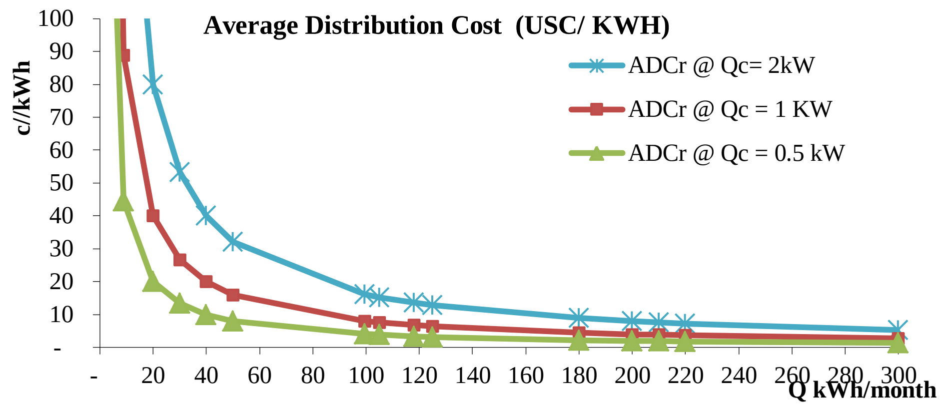

Figure 5-2 The average fixed cost curves at various capacity levels and a composite average ADCr curve at increasing capacity levels

Even if the LACr curve shown above in Figure 5-1 is a single U, the actual estimate will be for a series of parabolic curves at various reserve capacity levels of Qc, reflecting the relative peak capacity of the customers as in Figure 5-2. The lumpiness of grid investments and the economies of scale imply that it will not be possible to allocate costs at a very low capacity below ½ kW in a linear way (Gaunt 2003; 2005). Many customer specific costs such as metering, billing, customer service, and inspection costs are the same irrespective of the demand. Even the electrical equipment shows a very high level of scale economy as shown in Figure 5-3 for a transformer cost function for Orissa utilities.

The upfront cost function per kVA capacity of a transformer increases rapidly for smaller sized transformers and is not linear. At the low consumption of the very poor customers in the RGGVY program, 10 kVA transformers may be used to serve 20-40 poor villagers. Such an under designed power system is based on the assumption that customers will use only a few light bulbs often times provided to them free by the implementing agencies. This under designed system might reduce the total cost somewhat but the investment cost per kW is much higher than the $460/kW calculated in my model in Table 5-3.

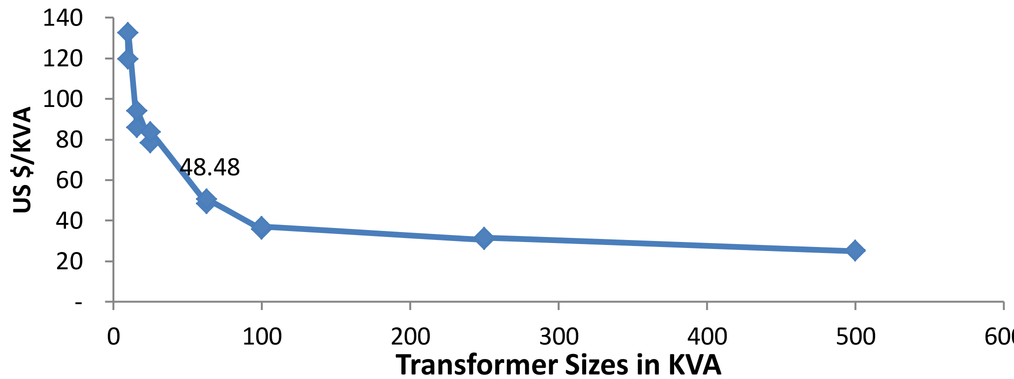

Figure 5-3 Economies of scale in installed capacity cost of a LV distribution transformer
Source: From the Orissa Electricity Regulatory Commission (OERC) 2007-2008 data

We are now ready to compute LACr in the next section.

Step 1.3 Computation of LACr

From Equation 5-1

$$LACr = Pg + ADCr.$$

Substitute for ADCr in Equation 5-9

$$LACr_i = Pg + Pc*Qc_i /Qr \qquad (5\text{-}10)$$

This equation shows that averages costs are a function of both capacity Qc_i and energy use Qr. We compute Equation 5-10 for our three capacities and different energy use as shown in Figure 5-4.

Table 5-5 Average Cost of Lighting Energy for Rural Use for Qr = 30kWh/month

Fossil-Grid Price at Minimum Peak Load		Rates		Cost of one 100W inefficient lamp left switched on the whole night can consume 30kWh/month.		
		Avg Capacity Costs Pc $/kW	Average Energy Cost Pg c/kWh	Average distribution cost ADCr= Qc*800/Qr	Average Cost LACr in c/kWh	Total Cost in $/month
Qc =	½ kW	8	18	13.3	31.3 ≈ 31	30*31.3=9.4
	1 kW	8	18	26.6	44.6 ≈ 45	30*44.6=13.4
	2 kW	8	18	53.3	72.3 ≈ 72	30*72=21.4

At the targeted 30 kWh/month, the average cost of electricity at ½ kW load is about 31 c/kWh at 1 kW load, it is 45 c/kW, and at 2 kWh load, it is 72 c/kWh. This is shown as the vertical dotted line in Figure 5-4, which represents the government target. As shown in Table 5-5, at the government target of 30 kWh with 1 kW of capacity and the computed unsubsidized prices, villagers with $100/month income would pay more than $13/month or more than 13% of their income.

Figure 5-4 shows the LACr for each capacity, which are obtained by adding Pg to the distribution cost (ADCr) in Figure 5-3.

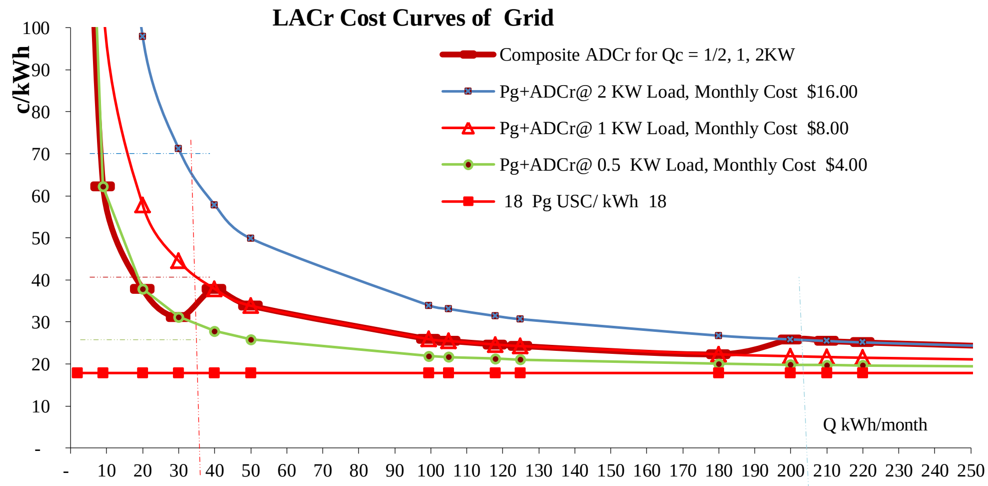

Figure 5-4 LACr based on the peak load capacity and monthly capacity charges

From the diagram it is clear to see that the targeted 30 kWh unit cost depends on the peak load. The lower the peak, the lower the capacity needed, and the lower the kWh cost. Unit costs also fall as a given capacity has a higher intensity of use. To derive a combined LACr, we need to know load profiles for various energy usage. Based on the JABA village experience, I propose the following jumps in peak capacity based on the energy consumption to develop the red dotted composite average cost LACr in Figure 5-4. This composite LACr curve shows a jumps at the Qr = 30-40 kWh/month when the capacity demand changes from LACr (½ kW) to LACr (1 kW) and another jump at Qr = 180-200 kWh/month from the 1 kW to 2 kW Qc curve. Such jumps in marginal/average costs are quite common due to the lumpiness of the local grid supply as the grid capacity cannot be as fungible as energy and capacity in wholesale markets. This composite LACr curve will be used for comparing costs for the grid with the SPV technologies and for answering question 4 to determine if the grid will be competitive by 2020.

This completes our computation and graphing of the grid average supply costs. We summarize all of these computations and intermediate variables for the reader in Table 5-6.

Table 5-6 Intermediate parameters and variables used in Q1

Groups	Variables	Description	Definition and calc steps
Variable Costs	Pg	Average grid energy cost	AVCr=Pg=Pw/(1+Ls%)
	Pw	Average wholesale market price for all 24 hours	Σ Pwi*Qwi/ΣQwi, i= 1-24
	Pw-on	On-peak wholesale price in c/kWh for On-peak hours 5 PM-11 PM	Σ Pw-on*Qw-on/Σ Qw-on
	Pw-off	Off-peak wholesale price in c/kWh	Σ Pw-off*Qw-off/Σ Qw-off
	Ls%	Rural electrical distribution loss %	35%
	Ef	The efficiency adjustment factor used to convert the wholesale grid market price to the loss adjusted average opportunity costs. The utilities often call this the electrical loss gross up factor	1/(1-Ls%)= 1/(1-0.35) = 1.54
	TVCr	Total monthly variable cost in $	Pg*Qr
	Pg	Average variable cost of the rural grid	Pg = 1.54*Pw-on
Fixed costs do not vary with the energy in short term but varies with the peak capacity demand	UC	Utility capital investment per customer (up- front distribution assets costs) e.g. wires, poles, transformers, switchgears per customer	Data from RGGVY (MOP 2008)
	CC	Customer capital investments (asset costs) e.g. meter installation, service ware	Data from RGGVY (MOP 2008)
	DI	Distribution total upfront investment per Customer	UC+CC
	CRFr	Capital recovery factor to convert upfront cost to a levelized annual payment for rural grid	14.5% for 25 years assets at 14% discount rate
	TUCr	Levelized monthly utility capital cost per customer	CRF*DI /12
	TCCr	Levelized total monthly fixed customer capital cost	CRF*TCC/12
	ORFr	Levelizing factor for annualizing the O&M cost @5% grid capital costs escalating at 5 % annually	7%
	TFCr	Levelized total monthly fixed distribution cost per customer	CRFr*DI/12
	TDCr	Levelized total monthly fixed distribution cost including O&M costs	TUC+TCC+TOM = TFC+TOM
	TCr	Total levelized monthly rural grid cost	LACr*Qr
	Qc	Peak load capacity of customers electrical appliances and devices	Expressed as maximum kW
	Pc	Average maximum capacity cost in $/kW/month	TCr/Qc
	Qr	Monthly electricity consumed by the rural customers electrical appliances and devices	Based on appliances
	ADCr	Average rural grid distribution cost per kWh	TCr/Qr
	ODCr	Overall monthly fixed costs for the distribution and customers assets for all customers	Σ Pc*Qc = ADCr*ΣQe summed over customers
Solar average and monthly cost calculatio ns	SI = CCs	Total SPV investment per household when Pwp is the price of SPV per peak-Watt and Qwp the SPV system peak-Watt capacity required per customer	CCs = Pwp*Qwp
	TCCs	Total monthly SPV capital costs per customer	CRFs*CCs/12
	TOMs	Total monthly O&M cost for SPV system	ORFs*CCs/12
	ORFs	Levelizing factor for deriving O&M cost as % of the SPV system capital costs	0.66% at 0.5% of capital cost escalating at 5%
	Ps	Average levelized SPV costs per kWh	TPVs/Qs
	Qs	Average monthly SPV electricity consumption	Qsp*5 hr/day*30days: Qsp = 200Wp for Q* = 30 kWh/month, 80W for Qs* = 9kWh/month
	TCs	Total monthly levelized SPV cost	TCCs+TOMs

The next step in this question will be to calculate the monthly and average SPV costs and compare them with the grid costs.

5.1.2 Step 2: Average cost of SPV electricity (Ps)

This step introduces modern SPV technology which is modular, small scale, safe to handle, and highly portable for rural applications. The cost computation for SPV electricity can be made with parallel computations using equations 1-1 and 1-7 but with much less complication. For purely off-grid SPV technology, there are no variable fuel costs, which are bulk power costs (Pg) for the grid, nor or there any utility electricity distribution costs. Thus the costs to consider are customer's own cost of SPV panels and related wirings and protection systems as solar investment cost per kW of the SPV capacity SI = CCs.

TCs = (1/12)(CRF*CCs +ORFs*CCs)

and

Ps = TCs/Qs

The details of the calculation of CCs and Qs are given below starting with an explanation of the data input. I followed the common utility approach of annualizing the solar investment cost CCs by the capital recovery factor CRF and O&M recovery factor ORFs and then dividing them by 12 as was done in the grid case.

CCs is the sum of the customer specific SPV panel costs and the wiring and protection costs a household might have. The costs of the house wiring and grounding cost are negligible for very low voltage (12 V DC) systems for rural homes as the system comes pre-assembled with wiring and switches, and small single panel solar systems require no elaborate protection. There will be some cost of installation of the solar system on roofs or in backyards, but these are minimal when local youth are trained to do the installation. The costs needed for installation of SPV panels are often included in the quoted costs of local SPV suppliers. The O&M costs will also be minimal with the proper customer training. Available surplus domestic labor in the poor households will allow the villagers to look after their own devices. I will thus ignore these non-SPV related costs. Now the only cost to consider is the SPV panel and mounting hardware costs for which the actual cost of SPV panels paid by us for our village project will be used. I start by using the SPV upfront investment cost, SI = $4500/kW of peak panel capacity against the $460/kW of grid capacity from Table 5-2. The kW in the case of the grid is the customer peak load where the SPV kW is the capacity of the solar panel to produce electricity at the standard 25 degree Celsius temperature.

Now for the usual process of converting a 25 year long-lived upfront overnight investment to monthly cost, I will use the same financial parameters of 14.5% CRF to arrive at the fixed monthly capital cost of $51.3/kW against the grid average cost of only $5.5/kW as computed in Table 5-7. Thus SPV costs are higher by about an order of magnitude (10 times) as shown in Table 5-7 for a 1 kW system. However, from here onwards the advantages of the grid gradually fades away and SPV cost advantages start to show up. I will show two important differences that make $ per kW an invalid comparison for off-grid SPVs.

I derive a levelized O&M cost factor of 0.66% from O&M costs for the SPV systems published in the literature. This SPV cost is much lower than the 7% factor for the rural grid. The monthly O&M cost is shown in line 8 of Table 5-7 at $2.4 for the SPVs compared to the monthly cost of $2.5 for the grid. Though this appears to be a small difference, in per kWh terms, it is significant. The grid O&M cost for 30kWh/month is over 8 c/kWh while the SPV O&M cost is less than 2 c/kWh (line13 of Table 5-7). The reason for this large discrepancy is that 1 kW of SPVs with 5 sun-hours a day can generate a much higher output of 150 kWh charging all villagers electronic and lighting devices, which have built in batteries. If 150 kWh is not needed, the villager can buy fewer panels at the same kW capacity cost as I have computed in the table. Although I have charged the 0.66% that is required for larger systems, my village O&M costs are overstated because I have a much lower or even free labor cost as users can easily manage their own SPV maintenance after the first year of training.

The bottom line of Table 5-7 shows that the grid average cost is higher than the standard rooftop SPV options. The cost of SPV electricity also varies widely depending on solar insolation and the type of solar panel used. For this theoretical analysis, I will assume a uniform cost of 38 c/kWh. This is the average cost of solar electricity without a battery backup except the batteries in the portable devices themselves

The last column in Table 5-7 shows the calculation for the highly distributed solar electricity generating system from an emerging new technology called organic solar PV. This technology has a very low efficiency of 5% at present, but the possibility of indoor application when painted over or attached to the appliances/or their outer cases can decentralize electric generation even from the roof-top/ground mount SPV systems to the appliances themselves. The power is generated from defused indoor sun or artificial lights and used at the point of use or stored in the appliance batteries for later use and can be ported anytime anywhere. This has tremendous applications in off grid homes as well as in military applications and is being popularized by few companies like Konarka Solar, which was started at the Massachusetts Institute of Technology (USA). The cost of SPV generation for this new technology based on my assumptions here is about 92 c/kWh. Although this cost appears to be a high, its potential is also high for both rich and poor. The consumer electronic goods powered by such SPV panels might appear to be novel goods for the urban rich in need of handy portable devices, and they might also help in powering high value devices for village community centers. With the portability and convenience of movement from one village to the other, such innovative technologies might turn out to be the least cost if the efficiency and social value of the ICET devices in health, education, lifestyle, job, and skill formation are considered.

Table 5-7 SPV average electricity costs TCs (without battery back-up) compared with the grid

	Technology →	**GRID**	**SOLAR PV**	
		1 kW Max Customer Capacity	**Roof Top Thin Film/ Crystalline**	**Dye Sensitized Organic** Modules for indoor consumer goods and small appliances (An Emerging Technology**)**
1	Upfront Investment Cost in \$/kW (DI, SI)	**460**	**4500**	**2000**
2	Useful life in yrs.	25	25	10
3	Capital Recovery Factor at nominal discount rate of 14% cost of capital	14.5%	14.5%	19.2%
4	Total capital cost (\$/kW-yr	67	652	383
5	**Monthly Capital Cost \$/month:**	5.5	54.3	32.0
6	O&M levelized factor escalating 5% annually ORFr(@ 5% for grid, ORFs@0.5% for SPV)	7.05%	0.66%	0.66%
7	Total O&M Cost in \$/yr	32	29.7	13.2
8	Rounded total O&M cost in \$/month	≈2.5	≈2.4	≈1.1
9	**Total levelized fixed SPV cost TDCr/TCCs in \$/month**	**8.0**	**56.7**	**33.1**
10	Capacity factor assuming (1kW load for 30 kWh/m) and 5 sun-hours/day in India	4.17%	20%	5%
11	Electricity used/generated/month in kWh	30	150	36
12	Average capital cost c/kWh	18.3	36.2	88.7
13	Average O&M cost c/kWh	8.3	1.6	3.1
14	**Fixed average Cost ADCr or Ps c/kWh**	**27**	**38**	**92**
15	Average Variable Energy Cost: Pg = c/kWh	18	0.00	0.00
16	**Grid and SPV cost LACr, Ps c/kWh**	45	38	92

Average energy generated from an SPV system (Qs) compared with the grid Qr: The average SPV cost is determined by estimating the energy produced per year with the assumption of 5 hrs/day of full sunlight (called sun-hours) at 1000/m2 insolation on a shadow-less horizontal solar panel surface. With the appropriate orientation and occasional adjustments with available domestic labor of a minimum of three times a day, the output can increase by 10-20% to 5.5 to 6 sun-hours a day. I take a conservative estimate of 5 hours/day, which is about 20% less than the maximum 5.5-6 hours possible to reflect the electrical efficiency losses in the wires, a mismatch of actual output with the nominal ratings of the panel due to higher temperatures, lower voltage of the battery compared to the panel, and dirt on the panel. I assume the same 20% capacity factor for both multi/mono crystalline or thin film SPV systems.[13]

The calculation in Table 5-7 above based on 1kW for the grid and for SPVs is a large size considering villagers consume 30 kWh or less. This high kW SPV panel is used as the normalized per kW base case and does not affect the average cost calculation of the SPV technology because costs are linear with little SPV economies of scale. The average cost will remain the same for SPVs no matter what the electricity consumption, but the grid average cost will be based on whether ½ or 1 KW peak load capacity is used. The grid average cost shown in the second column of Table 5-8 at a normalized one kW load is only for easy comparison with SPVs. This 1 kW grid capacity, however, is reasonable. For an adequate quality of service, a poor customer is likely to need one kW peak load for occasional use. For example, microwaves with falling costs may be more affordable to the poor, who will need it to heat or warm food quickly. An SPV-battery system allows this higher load depending on the Ampere-Hour (AH) battery capacity and type of battery.

5.1.3 Step 3: Cost comparison of SPVs with the Grid

In this step, I will compare the average and monthly costs of the grid with the respective costs of the SPVs. I will first compare the costs of SPVs with the costs of rural electricity when standard incandescent light bulbs are used for the targeted 30 kWh monthly coonsumption. Then I will consider efficient devices to compare the respective costs as that is future of the world and where the new energy use technologies are advancing fast.

Step 3.1 Average cost comparison without efficiency considerations

The SPV price of 38 c/kWh calculated in the previous step is based on a fairly high capital investment of $4500/kWp of solar panels available in the retail market. I use such a cost to not understate the cost of SPVs but know there is a strong potential for cost reduction with wholesale purchase.

For the JABA village, where we implemented the SPV project, dealers quote the lowest price of $4/Wp for a panel with an electricity output ranging from 40-80 Watts, compared to any

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[13] For the larger systems with multiple panels, the mismatch could be more severe because the SPV panels act as current sources. The minimum current generation out of the many panels in series determines the power out of the system. In rural India, I do not foresee use of multiple panels in series. In actual practice losses can be as high as 20% in the battery and solar charging systems. Battery charging cost is ignored here as it is same for the grid as for SPV.

other larger or smaller sized panels. The lower economies of scale of SPVs are reflected in the market place, where the price is quoted in $/Wp, whereas all the central grid capacity costs are in terms of $/kW. Further, it is possible to buy SPV panels of 40-80 Wp for $4.0-$4.5/Wp. If the requirement is for a higher watt of SPV panel and customers can afford to pay for them, multiple modules of this lowest cost size can be bought. Thus, the graph in Figure 5-5 shows the SPV cost as a uniform horizontal line at 38 c/kWh for a very low electricity output.

Figure 5-5 will now bring the grid and SPV costs calculated in steps 1 and 2 together to easily see which technology is cheaper and under what circumstances. It all depends on how much electricity is actually used and the peak load of the customers. When the peak load is high but consumption is low (the more likely case for the very poor), SPVs are cheaper and when the peak load is low, but consumption is high the grid is cheaper (the more likely case for the rich). As we have seen before, rural consumption is during peak hours needing more capacity for lighting, a cooling fan, or a popular TV program. On a hot evening with a popular TV program, the grid supplier must be ready with enough capacity to supply electricity making the grid expensive.

Notice there are three breakeven points in Figure 5-5 shown with circular star markers. Below about 20 kWh/month consumption, SPVs are clearly cheaper irrespective of the customer's peak loads. Between about 20 and 40 kWh/month the grid is cheaper only if the maximum load is limited by 1/2 kW. But the grid is not cheaper if the maximum load goes up to 1 kW from the ½ kW. From 40 to 80 kWh/month consumption at 1 kW peak load, the grid again comes out cheaper than SPVs. Beyond 80 kWh/month, the SPVs are clearly more expensive as the grid can supply lower average cost electricity due to higher utilization reflected in the economies of scale in the customers demand for electricity.

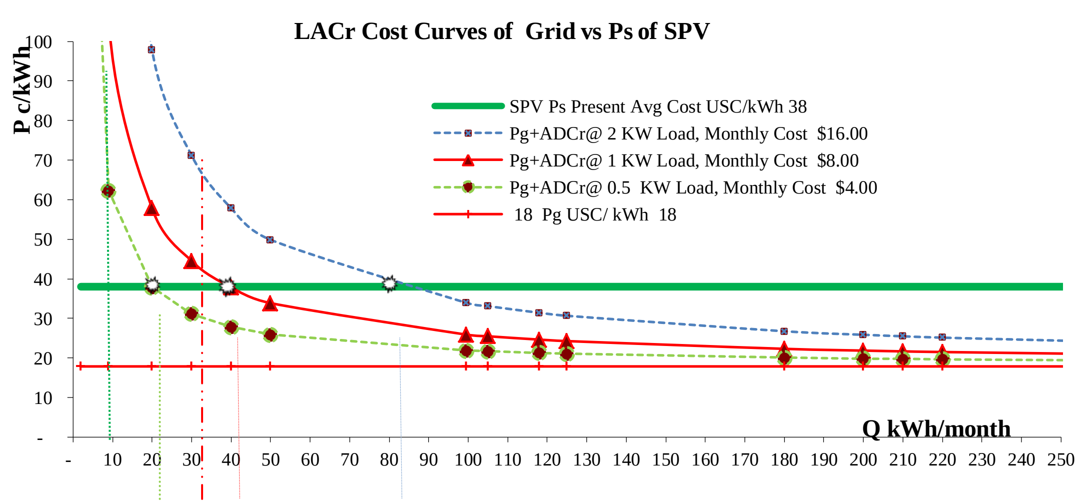

Figure 5-5 Cost curves grid vs. solar in a single Figure to show their competitive positions

Breakeven electricity consumption (Qe_i) for the i^{th} capacity (Qc_i) is where the cost of SPVs, Ps, equals the average cost, LACri, of the grid: or $Ps = Pc*Qc_i/Qe_i + Pg$

Solving for breakeven Qe_i yields

$$Qe_i = Pc*Qc_i/(Ps-Pg) \tag{5-11}$$

From the previous sections, Ps = 38, Pg = 18 c/kWh and the rounded Pc = $8/kW for capacity Qc_i for i = 1/2, 1, 2 kW. I convert kWh cost from cents to dollars and substitute P_i into Equation 5-11 to get the respective consumption levels.

Qe for ½ kW = 8*1/2/(0.38- 0.18) = 20 kWh/month

Qe, for 1kW = 8*1/(0.38- 0.18) = 40 kWh/month

Qe for 2kW = 8*2/(0.38- 0.18) = 80 kWh/month

I sum up the grid and SPV kWh and monthly costs for the targeted Qr* =30 kWh/month fossil-grid in Table 5-8.

For higher peak loads the grid is clearly more expensive at 30 kWh. The average cost of the rural grid will be 45 c/kWh at 1 kW peak capacity when efficient devices are not used. It could rise to 72c/kWh if high power appliances like heaters are used at peak capacity of 2 kW even for a few hours in a month.

Table 5-8 Average cost of inefficient electricity in rural lighting

Grid peak load capacity Qc_i	Fossil-Grid Costs compared with the SPV Costs for one 100W inefficient lamp left switched on whole night (100*10*30 = 30kWh/m)				
	Average Cost c/kWh		Total Qty kWh/month	Total Cost in $/month	
	LACr	Ps	Qs=Qr=Qr*	TCr= Qr*LACr	TCs= Qs*Ps
½ kW	31	38	30	**9.3**	11.4
1 kW	45	38	30	**13.5**	11.4
2 kW	72	38	30	**21.5**	11.4

For the lowest peak load, it appears that the grid is cheaper. SPVs will cost 38 c/kWh but the rural grid will cost only 31 c/kWh at ½ kW load. Thus if the rural poor use a low capacity of only ½ kW with relatively high consumption of 30 kWh, the grid will be cheaper than SPVs. However, notice that cost of that much energy consumption is $9.30 per month. We will see in the next section when we develop demand equations, very poor households with such low capacity demand will never consume that much power.

Furthermore, the same or better quality of service can be provided through the SPV systems using more efficient devices that will lower capacity below the feasible minimum 1/2 kW of the grid. For example, LEDs and CFLs not only use considerably less power, but they last much longer. I consider the costs of such efficiency improvements next.

Step 3-2: Comparison of Grid and SPV Average Costs Considering Energy Efficiency

I will start this calculation by designing an efficient and integrated ICET plan to meet much more than the basic needs of lighting that RGGVY envisages. Though the SPV price calculation was done for 1 kW peak modules to deliver 5 kWh electricity per day for the price comparison with the grid, a poor family may need a solar panel with much less capacity. I will demonstrate here how a 62 Wp SPV panel that generates only about 9 kWh per month can effectively meet all the basic needs of lighting (2*10W for 5 hours), cell phone charging (3W for 2 hours), viewing TV (20W for 5 hours), or a cooling fan (20W for 5 hours). My computations are vindicated by a previous study by IEA (2001) that has shown that poor households in urban area use only 7-9 kWh/month for lighting, if they have to pay for the full costs of electricity. In rural areas, with incomes lower than in urban areas, I do not expect the consumption to be much higher.

Table 5-9 summarizes how such efficient devices would need only 9.18 kWh/month and a 62Wp solar panel at 20% capacity factor can generate this electricity. We note here the load factor of appliances of about 5 hours a day perfectly matches the capacity factor of SPVs. The battery storage can be reduced by maximizing day time use and storing surplus electricity in built-in appliance batteries or in rechargeable batteries for cloudy days or night times for lighting and TV. Rich people already use such a battery system even when they are grid connected.

Table 5-9 The efficient appliances are used in the off-grid SPV systems

Appliances	**Power ratings (Watt)**	**Number of devices**	**Total Power (Watt)**	**Hours/ day**	**Total kWh/day**	**Equivalent inefficient device used in the rural grid kWh/day**
CFL	10	2	20	5	0.100	2*40W*5h = 0.4
Cell phone	3	1	3	2	0.006	0.006
Small TV and Fan	40	1	40	5	0.200	2*60W*5h = 0.6
Total Power and Energy			61		0.306	1.006
Monthly electricity need Qs			9.18 kWh			30.18 kWh
SPV capacity required with 20% capacity factor			0.306/24/20% = 0.062 kW= 62Wp			1.006/24/20%=210 Wp

Wp is the peak-watt rating of a solar panel at insolation of 1kW/square meter at 25^0C.

The grid average cost for electricity is computed in Table 5-10 with both inefficient appliances (using 30 kWh/month) and efficient appliances that provide similar services (using only 9 kWh/month). The average grid costs, if more efficient appliances and lighting devices are used, increase dramatically to 62 c/kWh and 106 c/kWh for the 1/2 and 1 kW grid capacity. As

SPV devices are not lumpy or idiosyncratic (the modules can be sold off, or used for other purposes), the average costs of SPVs still remains at 38 c/kWh. Here we see that efficiency works against the grid due to the fixed cost involved in the grid supply.

Table 5-10 Average cost of lighting energy for rural use

Uses per month Technolgy		Inefficient appliances 30 kWh/month (1)	Efficient appliances 9 kWh/month (2)	Monthly cost $/month TCs/r	Efficiency Price Ratio
Comments about effciency		18 +800 Qc/30 c/kWh	18+800*Qc/9 c/kWh	LACr/Ps*9 kWh	(2)/(1)
Rural grid	Qc = ½ kW	31	62	62*9 =5.58	2
LACr	Qc = 1 kW	45	106	106*9 = 9.54	2.3
Off-grid SPV Ps		38	38	38*9 =3.42	1.0

(2) Modern LED and CFL and most ICET devices can power a two room house with just 9 kWh/month.

The monthly costs in the table for SPVs is only $3.42/month while the grid cost will be almost double at $5.58/month. The use of efficient appliances doubles the grid average costs, but SPV average cost remain the same. Thus on monthly cash outlay basis, a poor customer can have less total and average costs compared to the grid alternative. In the anlaysis so far I have ignored the additional costs of efficient appoilances. On the high cost of efficient appliances, it may be noted that the costs of the CFL and modern appliances are falling sharply. The annual energy cost saving is (9.3-3.42)*12 = $72 which can recoup the additional costs of the efficient appliances in less than 2 years at today's price. As shown in Table 5-11 below, only using the marginal energy cost of 18c/kWh, the government which is subsidizing energy supply can instead encourage effcient devices and recover the upfront additional investments in 2 years.

Table 5-11 The self-financing nature of the cost of efficient appliances used in the SPV system.

Appliances	**Number of devices**	**Costs in $**	**Inefficient device costs $**	**$ Difference in cost could be invested by government**
CFL	2 (each cost $3 and lasts 5 Years)	6	5 (each cost $0.25*10 numbers required for 5 years)	1
Cell phone	1	20	20	0
19 inch LCD TV	1	200	110	90
A small DC Fan	1	20	10	10
Total cost		246	131	101
Annual electricity kWh saved from table 5-10	(30-9) kWh/month*12 = 252 kWh			
Annual $ saved using only efficiency adjusted energy marginal cost of 18 c/kWh	18*252kWh = $48.6			
Breakeven years for additional cost	101/48.6 = 2			

Portable Solar CFL/LED lanterns, fans, and cell phones using a rechargeable battery are essential for both the rich or the poor in most Indian rural homes, electrified or not and they are valuable for their flexibility of use in homes, on farms, and on streets. The increasing level of efficiency in the last decade have made it possible to design many different varieties of portable and wireless electrical appliances such as small power tools, kitchen and garden tools. The costs of efficiency, ignoring the other values of these appliances such as the portability, longevity, and resources saved in operation and maintenance, are very low as explained below through two block diagrams in Figure 5-6. The left block shows the costs and quantities of inefficient energy use and the right shows efficient energy use.

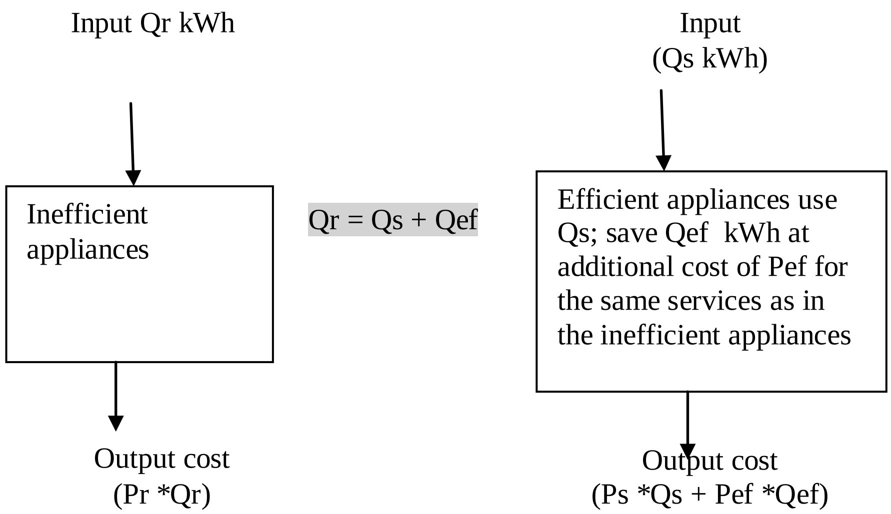

Figure 5-6 The effective price with efficiency is much lower Pe = (Ps*Qs + Pef*Qef)/Qr

The effective price of the energy, when the efficiencies of the solar powered devices are factored in, can be given by the equations

$$Pe = (Ps*Qs+ Pef*Qef)/(Qs+ Qef) = Ps*qs\% + Pef*qef\%$$

Where, qs% = Qs/Qr = the share of energy SPVs use compared to an inefficient appliance and qef % = Qef/Qr or the share of energy saved through efficiency technologies. The prefix “ef” stands for efficiency and “s” for SPVs and “r” for the rural grid.

From the market data on price and lumen equivalencies, we know that a 100 Watt Edison incandescent bulb is cheaper but has a short life, a 25W CFL has a longer life and a 13W modern high lumen LED bulb has a very long life but all of them provide approximately 1500 lumen output. The price of efficiency, Pef, for a CFL or an LED bulb when replacing the inefficient incandescent bulb can be computed as shown in Table 5-12. This table summarizes average cost calculations of rural fossil-grid for ½ kW peak load to power 100W incandescent Edison bulb and for SPVs to power efficient 13W LED lights and 25W CFL.

For the time being, I will ignore the additional operating and environmental benefits of durable and low power consumption devices and just concentrate on the power savings. The new CFL lasts 10 times longer (5years) than an incandescent while using 1/4th the energy. The price or cost of energy efficiency (Pef) for the CFL is given by the extra cost of the CFL divided by the extra energy purchased for the incandescent Edison bulb. I find this average cost of efficiency of an CFL a negligible 0.3c/kWh as shown in line 8 in Table 5-12. Likewise, the average cost efficiency of switching from an incandescent bulb to an LED has been indicated as the extra annual cost of LED divided by the extra power purchased by incandescent bulb. The Pef for the LED varies from 3-4 c/kWh depending on the durability of the LED purchased as shown in lines 9 and 10 in the table.

The CFL light has a lower cost of efficiency compared to the LED when we ignore the other rural benefits of LED lights and the disposal costs of mercury containing CFLs. The high upfront investment also penalizes the LED, despite its longer life. However, even with the CRF of 16.3% (CoC 14%, 15years life), the average cost of LED is only about 4 c/kWh, much lower than the electricity supply cost from any other source. Clearly as can be seen from the last column and the last four rows, the effective costs of efficient lighting is lower than 4 c/kWh and much lower than the rural grid and SPV generation costs.

Table 5-12 Cost of efficient lighting is about 1-4 c/kWh

Col. number	Row Numbers	A	B	C	D	E	F	G	H	I	J	K
	Supply (S) and Demand side Load (L) Technologies	**Capital Cost**	**Year**	**CRF**	**Annual Cost in $** A*C	**Rating (in Watts)**	**Daily use in Hrs**	**Annual kWh/Yr F*365**	**Fixed Capital $/kWh D/G**	**Fixed O&M $/kWh#**	**Var Energy $/kWh**	**Total Avg Cost H+I+J**
1	Rural Grid (S) 1/2kW load	230	25	14.5 %	33.46	500	2.00	365	0.09	0.04	0.18	0.31
2	Edison bulb (L) unsubsidized	0.25	0.5	220 %	0.55	100	5.00	183	0.00	0. 01	0.31	0.32
3	Edison bulb (L) subsidized	0.25	0.5	220 %	0.55	100	5.00	183	0.00	0.01	0.03	0.04
4	SPV (S) per 1/kW	4000	20	15.1 %	603.94	1,000	5.00	1825	0.33	0.05	0.00	0.38
5	5 year life CFL (L)	3	5	29.1 %	0.87	25	5.00	46	0.03	0.00	0.38	0.42
6	15 year life LED (L)	40	15	16.3 %	6.51	13	5.00	24	0.01	0.00	0.38	0.39
7	10 year life LED (L)	30	10	19.2 %	5.75	13	5.00	24	0.01	0.00	0.38	0.39
8	Efficiency Pef (CFL 5 yrs-Edison)	Annual cost incurred//energy saved with respect to Edison light bulb			0.32	(75)	-	(137)	0.003	-	0.00	0.003
9	Efficiency Pef (LED 15 yrs-Edison)				5.96	(87)	-	(159)	0.04	-	0.00	0.04
10	Efficiency Pef (LED 10 yrs-Edison)				5.20	(87)	-	(159)	0.03	-	0.00	0.03

The bottom line of this simple analysis is that efficiency has the lowest cost and can bring down the weighted average cost of solar power. The CFLs/LEDs have additional benefits for rural use. The CFL has a longer life, and though it is more expensive, it reduces the required battery capacity and thus makes portability possible, which would have been very expensive, awkward, hot, and unsafe with incandescent bulbs. An LED has the longest life, is shatter proof (making it immune to vandalism of street/outdoor lights in rural areas), requires less maintenance, and has a fast response with directional property. With the directional nature, the LEDs can focus illumination to the useful, display or reading spaces reducing unnecessary illumination at undesired places called lighting pollution. This reduces the total lumens and wattages of LED lamps thereby requiring reduced battery capacity, which in turn decreases charging time and enhances the SPVs capacity to charge it. Further, they are completely pollution free with no mercury. These properties and the tremendous improvement in the application of the efficient devices and solar power together create additional value for portable applications in rural areas. The popularity of the festival lighting, garden lighting, street/traffic lighting, and reading lights as well as the LED TVs and pocket projectors illustrate such advantages of the LEDs. Many such outdoor and indoor LED devices are being powered through solar and battery technologies in developed countries where the grid has no such reliability or availability problems as in rural poor economies. This will further justify that these high efficiency devices will be helpful for rural poor economies to directly transition to a new world of solar LEDs.

Extending this analysis more generally, the literature (NARUC 2009; Energy Center of Wisconsin 2009) indicates that the cost of efficiency varies from zero to 4 c/kWh for many common applications. Used conservatively, the maximum cost of efficiency Pef = 4 c/kWh, with quantity ratio qs 20% due to efficiency, we can find the effective electricity price at the input of an efficient appliance Pe in terms of the price at the meter Pr.

If qs % = 20%, and qef = 80%

Pe = 38*20%+4*80% = 10.8 c/kWh

This is cheaper than the grid delivered at the cost of 31 c/kWh (for ½ kW capacity) or equivalent to the urban grid price of 10-12 c/kWh. Thus, efficiency can reduce the overall costs of SPVs by one third in rural applications and make them commercially self-sustaining. Similar energy efficiency is hard to come by in a grid environment due to the extra costs of metering and administration. Besides when these efficiencies are enforced, the grid supply cost is no less than the average cost of SPVs; rather it doubles to 71c/kWh as shown in Table 5-10. A mini case study from the JABA village in Chapter 6 will provide more practical evidence for these price and non-price factors. Before I explain the demand side of the SPVs, I will deal with the much higher costs of the SPV-grid that the Indian government is now encouraging under the Jawaharlal Nehru National Solar Mission (JNNSM) announce at the beginning of the year 2010.

Comparison with off-grid SPV shows the SPV-grid the most expensive option.

The excess costs of the SPV-grid can be easily explained by assuming that the government will have to pay a 38 c/kWh feed-in tariff to SPV-grid suppliers. At the same time, in order simultaneously to deliver this power to 80 million customers, the government will have to extend the rural grid. It will in effect buy the SPV power at 38 c/kWh at the wholesale level instead of the wholesale market price of 12 c/kWh for the fossil-grid. The SPV-grid will be feeding power to the rural homes with 35% electrical loss at total efficiency adjusted marginal energy cost of 1.54*38 = 58.46 c/kWh. The rural average distribution cost ADCr is a minimum 13.33 c/kWh for ½ k load. Thus the total delivered cost of the SPV power through the rural grid is 71.79 or nearly 72 c/kWh while 38 c/kWh will be the costs of efficient off-grid electricity. As discussed above, efficiency is not a good friend of the grid as it increases the average cost of the grid using fossil or SPVs as the energy source. Further, as in the fossil-grid it is difficult to enforce efficiency without much expensive metering and administration.

I will assume that the SPV-grid has no emission related externality costs. To compare the SPV-grid costs to the fossil grid, it is, therefore, necessary to account for this benefit by pricing emissions in some way. The emission related costs can be collected as a market based emission tax (ET) on all polluting generators. Thus we can assume for simplicity ET = 0 for the SPV grid but is about 4 c/kWh for the fossil-grid based on a carbon price of 40 $ per ton of CO_2 and other externality costs discussed in the literature review. Thus, the SPV-grid costs are 71.79 c/kWh against an emission adjusted grid costs of 37.95 c/kWh. The SPV cost of 38 c/kWh is shown in Table 5-12 and graphed in Figure 5-7. Emission cost with the loss adjustment is 1.54*4 = 6.15 c/kWh. When this is added to Pg =18.46 c/kWh and AFCr=13.33 c/kWh for 30 kWh consumption at ½ kW, the emission adjusted grid cost is close to 38 c/kWh, the same as the marginal wholesale cost of the SPV. Thus even with dramatically higher emission costs, the fossil grid is still much cheaper than the fully loaded costs of the SPV-grid. But the off-grid costs are very competitive as shown below and in Table 5-13.

On the positive side, off-grid SPVs have neither losses nor distribution and externality costs. They can be the least cost and most efficient option with same constant 38 c/kWh at the customer door step. Further by incorporating conservative efficiency costs of 3 c/kWh, the consumption can be reduced to about10 kWh/month and the weighted average costs can be reduced to about 15 cents/kWh. (38 *10/30+ 3*20/30 = 15).

The total cost of the SPV grid is $9.8 billion higher than the cost of the rural fossil-grid per year for supplying 28.8 billion kWh of SPV energy (for 30kWh/month*80 million*12) as shown in red in rows 8 and 12 of the SPV-grid column in Table 5-13. While the excess cost of the SPV grid with reference to the rural grid is $9.8 billion, the off-grid SPV electricity is $8.7 billion cheaper than the fossil-grid. The net financial benefit of $19.23 per month per household is as shown in the table if off-grid SPVs are promoted instead of the SPV-grid. I have also added the costs of the SPV mini-grid, which will be more expensive than off-grid SPVs due to LV distribution metering and billing costs not present in the off-grid SPVs. The mini-grid cost is assumed to have distribution costs at about 50% of central grid and 50% electrical loss with17.5% efficiency loss factor 1/(1-17.5%) =1.22.

Table 5-13 Over $18 million in off-grid SPV cost savings compared to SPV-grid in India

	Description	**Notations**	**Fossil-Grid**	**SPV Grid**	**Mini grid**	**Off-Grid SPV**	**Note**
	Benchmark Efficient grid wholesale price	Pw	5.00				For example price in more efficient market in the USA
1	Amount of energy supplied	Qe	30.00	30.00	30.00	10.00	Gird encourages inefficiency/Off-grid uses efficient appliances
2	India wholesale price	Pw-on	12.00	38.00	38.00	38.00	Indian wholesale market less efficient/Renewable SPV cost same in grid or off grid
3	Electrical loss adjustment	35%	6.46	20.46	10.23	-	High electrical losses 35% for SPV grid, (factor 0.54); 18% for mini-grid (factor 0.22).
4	Marginal cost Pg,/Ps	1.54*Pw-on	18.46	58.46	48.23	38.00	
5	ADCr	30@kWh/m	13.33	13.33	6.67	-	High rural distribution cost ADCr for very long lines but very low consumption,
6	Emission tax US$/40 Ton CO_2	ET- 4 cents /kWh over Pw	6.15	-		-	Emission loss adjusted for grid and negligible for SPV. Also assumed 0.9kg CO_2/kWh from CEA (2007a; 2008) and accounting many other pollutions only 1 c/kWh.
7	LACr at Qr*	@30 kWh/m	37.95	71.79	54.90	38.00	Rural SPV grid is the most expensive and off-grid SPV average cost is same as that of conservatively estimated rural fossil-grid
8	Difference in avg cost	Fossil grid is the base price	-	33.84	16.47	0.05	
9	% increase in the average cost		-	90.00 %	50.00	0.14%	Over and above the fossil-grid cost of 37.95 c/kWh as base
	Q, Monthly usage/household	kWh/month	30	30		10	Off-grid SPV use only 1/3 energy
	P, Rounded weighted average costs	c/kWh	38	72	54.90	15	With device efficiency off-grid SPV much cheaper
10	Monthly Cost TCr	P*Q= $/month	11.38	21.54	16.47	3.80	Conservation and efficiency off-grid can be less expensive in terms of monthly costs by $21.54-$3.8= $19.23
11	Increased Cost/month	$/month/customer		10.15	3.58	(9.08)	Monthly household saving (10.15+9.08) = $ 19.23
12	Annual savings for 80 million households	Billion $/year		9.80	3.44	(8.70) billion	Annual national saving 18.5 billion Row 11*12months*80m customers

As calculated in the last row of Table 5-13, the additional cost of the SPV grid is $9.8 billion but the benefit of the off-grid SPVs is $8.7 billion compared to the fossil-grid with emission costs internalized. The net additional costs of the SPV grid over and above the off-grid SPVs are therefore $18.5 billion a huge amount that the government has to find a way to raise from somewhere.[14] To produce 28.8 billion kWh solar electricity requires installation of 16,000 MW of SPV-grid systems at a 20% capacity factor. Rural households might need just 80W*80 million homes = 6400 MW installed capacity with the balance of 10,000 MW going for rural diversified production and farming instead of the current subsidies to the SPVs and fossil-grid. This is a huge SPV capacity, with a global annual production about half of this. With learning curve effects such an increase suggests that the assumption of 38 c/kWh is very conservative. Thus the need for high subsidies to the SPV-grid to bring down costs of SPVs is not tenable, while the same expansion can also be done subsidy-free using off-grid rural SPVs as I will show in the answer to the next question.

To answer Q2, I have developed a composite cost curve for the grid adding wholesale power costs adjusted for inflation to rural distribution costs. Distribution costs depend on-peak capacity used as well as monthly consumption of electricity. I take a capacity of 1/2 kW up to 30 kWh monthly consumption, capacity of 1 kW for consumption from 30 kWh to 180 kWh, and a capacity of 2 kW for consumption of >180 kWh. I have already developed SPV costs of 38 c/kWh. I found the grid to be cheaper for consumption greater than 40kWh/month, but more expensive than SPVs at all lower consumption except for 20-40 kWh with a capacity of 1/2 kW. However, for 1/2 kW range where the grid is cheaper the monthly bill is higher than I expect the rural poor will be willing to pay. I also show that a cheaper solution would be to put in more efficient appliances reducing capacity further, which would lower the monthly bill to a more reasonable range and once again make SPVs cheaper than the grid. In the next section, I will support this last assertion by developing demand curves for the Indian rural poor to determine their willingness to pay.

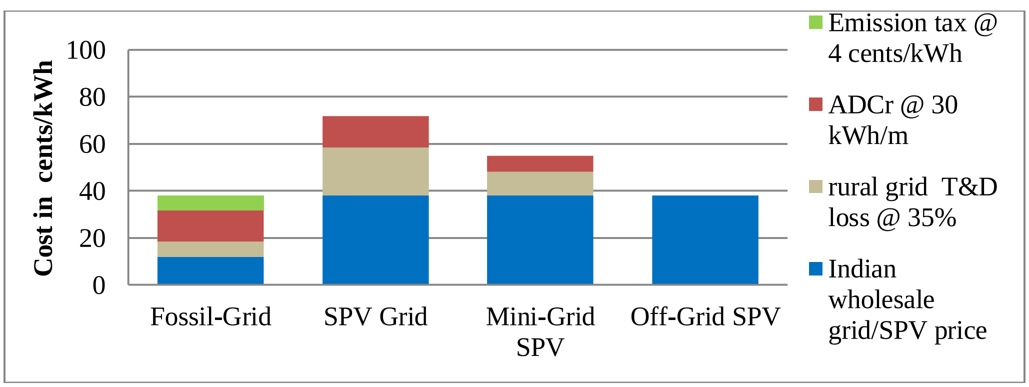

Figure 5-7 Total marginal costs of fossil-grid, renewable grid, and off grid SPVs

[14] Though I have added an indicated emission cost at 4c/kWh to the above analysis for comparison with the fossil-grid system, this saving of the off-grid over SPV-grid is independent of the emission costs.

5.2 Q2 - Can Fossil Grid or Off-grid SPV Provide Subsidy-Free Electricity in Rural India?

Though the analysis above shows that at a lower level of consumption, the grid is expensive, the answer to the question of whether the grid or SPV electricity is actually cheaper is still ambiguous as we do not yet know the affordability and actual demand level of the villagers. The actual demand level of the villagers derived from data in my case study will show if they have the willingness and ability to pay.

Answer: *The fossil grid technology cannot provide subsidy free electricity based on the low demand and income level of the average customers in the sample village of Orissa from which data was collected. The off-grid SPV electricity can be subsidy free at any level of demand. There will always be a demand supply equilibrium due to the modularity and constant average costs of the SPVs.*

5.2.1 Demand curve analysis

In this question, I will compute the demand curve of a village in India with the data collected from 2003 to 2008 on income and energy use. The demand curve for electricity, which is a function of income and electricity price, will be presented. The demand curve will be compared with the grid and SPV cost curves to find any possible market clearing price. If there is no market clearing demand and supply equilibrium, I will conclude that a subsidy is required for the market to clear.

Assumptions:

- Demand for electricity (Qe) for rural use is a function of Income (Y) and the price of electricity or the electricity equivalent of kerosene (Pe).
- The JABA villages in Orissa from which the data have been collected represent the rural poor in India. The economic situation in this village is more or less comparable to the average of rural India.
- The electricity equivalent of kerosene is computed based on the lumen output of a 5W incandescent bulb.

Background information of JABA village from which the data has been gathered for this model:

- Electricity, though a substitute for biomass and solar heat, is more expensive and rarely used for cooking, heating, drying and other thermal energy use in rural India. Thus, electricity demand does not include heating demand.
- Kerosene is a lighting fuel for 5 hours a night in non-electrified homes and is also used in

electrified homes during the frequent power outages.

- Even with the high prices, subsidies may not be required, if the level of electricity consumption is so low that the total cash outlay is a small fraction of household income. A small amount of electricity can meet many of the essential needs commensurate with the income and demand levels of poor households as expressed by their willingness and actual payment capacity. The consumption of kerosene for evening lighting is very expensive, as we will see later, even with the subsidized price. Still poor households do buy and pay for it.
- As can be seen in Figure 2-1 below, the meeting point of demand Dr in the supply curve LACr at price Pr and quantity Qr is subsidy free. This is also the equilibrium output level of the demand curve and the grid, which is inferior to the SPV price at Ps for Qs. Interestingly enough, the average price and the total costs of supplying the fixed government target quantity of Qr* could be very high in a much lower demand curve D_L as the price P_L is very high or indeterminate and the subsidies could be huge.

Figure 5-6 shows all the demand functions D_L, Dr, Dh (repeated from Figure 5) that will be estimated in this question. These functions with the associated variables as already defined in Table 5 are repeated with addition of price of kerosene in Table 5-14.

Table 5-14 Variables and demand equations to be estimated and determined

Variables and Functions	Variables	Description
High Demand Price and Output	Dh	High income (Yh) demand function
	Qh	High income equilibrium consumption
	Ph,	High income equilibrium price
Low Income Rural Demand Price and Output	Dr	Rural income (Yr) demand function
	Qr	Rural income equilibrium consumption
	Pr	Rural income equilibrium price
Very Low Income Demand	DL	Very low income (YL) consumers demand
	QL, PL	Market equilibrium values is indeterminate
	Qr*	Very low income consumption is administratively fixed by government often with inefficient appliances
Kerosene Supply	Pk	Cost of subsidized kerosene in c/kWh

In all cost studies and in the popular literature, when a point is made that grid power is cheaper, the implicit assumption is that the consumer has enough income and is using enough power. However, to check this assumption for Q2, I will estimate the demand curves and show the equilibrium prices both graphically and algebraically at various levels of incomes. I will show, through the estimation of the demand curves from the actual data in the Orissa village, that for poor households the grid cannot work without subsidies while SPVs can.

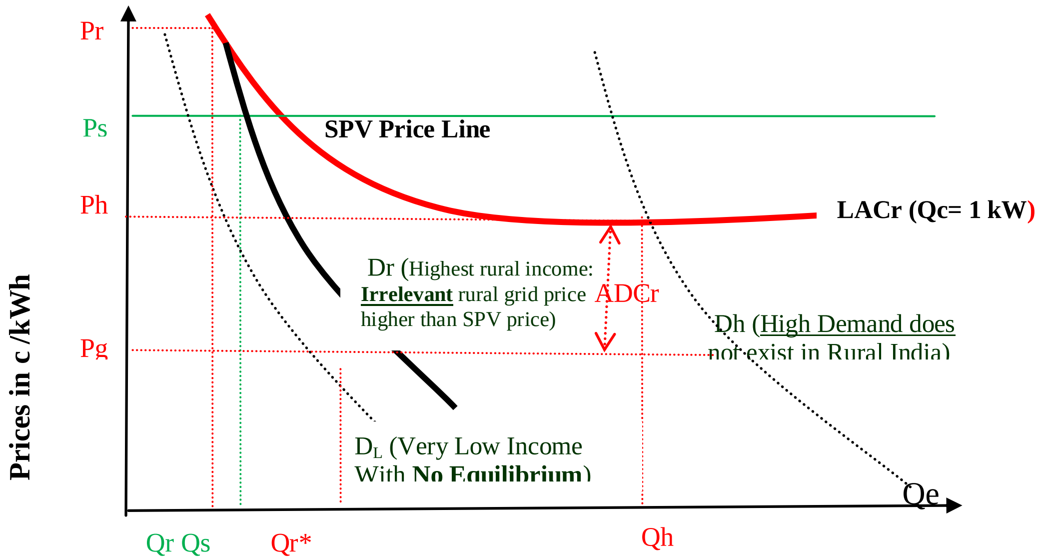

Figure 5-8 Equilibrium of SPVs and Grid for Poor Homes

We will have a four-step process in the calculation of rural demand and the determining the price and consumption equilibriums as listed below.

5.2.2 Step 1: Market definition and the Demand Model

Step 1 a. Define the rural electricity market and the demand model

Electricity demand for homes is derived from the demand for lighting, fans, TVs, electric appliances and gadgets (ICET) for health, education, lifestyle comfort, and entertainment (UNDP 2001, Barnes 2002, Choynowski 2002). To estimate their demand, I will adopt a semi log demand Equation 5-6 from Choynowski (2002) with an added income term (Y) to measure how consumption varies with income growth. To my knowledge no such estimates for lighting demand exists for rural Indian villages. The semi-log relationship demand curve is given by

$$\text{Ln Qe} = a + bPe + cY \quad (5\text{-}12)$$

$$\text{Or, Qe} = e^{\wedge(a+bPe+cY)} \quad (5\text{-}13)$$

The inverse demand function from Equation 5-12 will be useful in this study and is given by:

$$Pe = -(1/b)*(a+cY- \text{Ln Qe}) \quad (5\text{-}14)$$

I compute Qe by adding the kWh of electricity consumption to the kWh of kerosene consumption, used by the rural poor for lighting. Kerosene is also a popular fuel during power outages even in electrified homes. For this purpose, the kerosene consumption was first converted to equivalent electrical energy for lighting. The price Pe is then calculated as consumption weighted average price of electricity and kerosene.

The demand curve 5-12 will then measure the total demand for electricity at the price of electricity (Pe) in c/kWh and the monthly household income (Y) in $/month. The parameters a, b, and c will be determined from the regression of energy-use data on income and prices.

The total demand for a village is the aggregate of the individual household demands and the community demand. Instead of summing up all demand to find a market demand, I will derive household level demand curves for electricity. Then the household demand model can be comparable to the household level grid supply cost curves derived in Q1.In this household market, the grid will be in competition with the alternative SPV electricity to establish its long-term position, if it can.

STEP 1.b Compute the effective market price of electricity and kerosene lighting

Kerosene, though an off-grid fossil fuel, has about a 75% subsidy to make it affordable for rural lighting of all homes. This is not only a lighting fuel of choice for the poor who can buy a small amount each day as and when needed, it also serves as the only available backup to the unreliable rural grid for most poor and even rich homes with no access to modern inverter and battery based systems used in the cities. The cost estimate of operating kerosene lamps is therefore important in understanding the price impacts on the lumen consumption both in the poor as well as in the not so poor homes. The non-poor households are also found in our case study to be using more kerosene for lighting during the essential evening study hours and on festival nights compared to that used by the poor households.

The price of electricity is subsidized and does not vary in rural India. The same is also true for kerosene as a lighting fuel. Although prices do not vary, I could calculate different implied prices of electricity for different households electrified or not for their varying consumption of kerosene for evening lighting. This price calculation requires the computation of the average cost of kerosene lighting in terms of the c/kWh equivalent of an incandescent bulb. This computation is given below.

The cost of kerosene lighting: The supply costs of kerosene in villages are high, not only from very high costs of transportation and storage but also from the hidden costs of kerosene lamps in the time lost in daily chores to fetch kerosene from the shop, clean lanterns, attend to the wick and mantles along with its attendant air pollution and fire hazard. Even if the scale economy of kerosene is not that prominent, at longer distances far from commutable roads, kerosene is very expensive to buy at regular intervals, and the amount of labor involved is significant. The cost of kerosene in terms of c/kWh is also high due to the inefficiency of kerosene lamps that deliver less than 75 lumens, equivalent to 5 Watts of an incandescent electric bulb from the consumption of 0.1 liter per day for 5 hours. This calculation is shown in Table 5-15

The cost of electricity, as shown in the above table, is the cost of the subsidized kerosene lighting and will be approximated at 90 c/kWh. Though kerosene is an expensive fuel compared to the grid, the poor still use kerosene when they cannot pay the fixed cost of electricity access and devices. The grid is unreliable and Edison's bulb cannot be carried by hand through the backyard and streets. What matters the most is not the price but the portability and the affordability in terms of the budget share of their cash income, which is highly volatile from zero to a few dollars a month. Kerosene fuel has the advantage of allowing a poor village woman to match the supply of lighting with her demand that ultimately depends on her daily cash income. Buying kerosene may not be necessary if she can cook and feed her family before dusk and the kerosene expense of about 5cents can be saved that day.

Table 5-15 The cost of kerosene light equivalent of Edison bulb in c/kWh

	Description	Subsidized	Unsubsidized
1	Lamp capacity 5W for 5 hrs (Wh/day)	25.00	25.00
2	Lamp consumption liter/day	0.10	0.10
3	Kerosene price Rs./liter	10.00	30.00
4 (2*3)	Kerosene expenses Rs./day	1.00	4.00
5 (1*2/1000)	Edison bulb energy equivalent kWh/liter	0.25	0.25
6 (3/4)	Kerosene price Rs./kWh equivalent of Edison bulb	40.00	120.00
7	$ Exchange rate	45	45
8	Kerosene lighting price c/kWh	88.9	267

The effective price of electricity when kerosene is also used: The true cost of rural lighting is the average of using both grid electricity and kerosene. The villagers use different proportions of the rural grid and kerosene lighting depending on the duration of power outages, their incomes, lifestyles, and need levels. The prices of equivalent electricity can be computed as the weighted average of the costs of kerosene and electricity measured in c/kWh of electricity equivalent. For example, the cost faced by one rural household using only kerosene is 90 c/kWh for the light output at 0.25 kWh/liter of kerosene. The price faced by another electrified home for using only the grid electricity is 3 c/kWh. If an electrified home uses 3 liters of kerosene in addition to the 30 kWh/month of electricity, the total electricity equivalent of the energy is 30+0.25*3 = 30.75 kWh at the weighted average cost of 3*30+90*0.75/30.75 = 157.5/30.75 =

5.13 c/kWh. An un-electrified household faces the electricity price of 90 c/kWh and a house not using kerosene at all will have a price of just 3 c/kWh. In this way, I get price variation from 3 to 90 c/kWh. These price variations could be seen in the scatter plots in Figure 5-7.

5.2.3 Step 2: Demand modeling of poor homes

Developing my demand estimate will take two sub-steps. The first sub-step includes the data collection, processing, and description from the case study, and the second gives the data analysis and regression to compute the demand curve for rural electricity at various income levels.

Step 2a Data collection and description: The JABA village has three distinct groups of electrified and non-electrified households. The high-income group, having an income of about $400 /month is completely electrified. The two other groups are poor with an income of about $50 /month. One of these groups belongs to the backward section known as scheduled castes SC, which has grid electricity, the other does not. In both groups, there is very little contribution of grid electricity to income, though it might provide social recognition and a better lifestyle. The data collected from these three income groups and the average electricity and kerosene use and the income usage are summarized below in Table 5-16 (ported from case study chapter's Figure 4-5). The electricity price has been assumed to be 3c/kWh but for the kerosene users the equivalent price per kWh is high and computed as 90 c/kWh for the subsidized kerosene or 10 Rs/liter.

Table 5-16 JABA village average group wise data for household electricity demand modeling

Group Name	Primary Income Sources	Fuel Sources	Number of households	Consumption kWh/month (Q)	Price c/kWh (P)	Income /month (Y)
Electrified Poor	Labor	Electricity	32	70	3	55
Non-electrified Poor	Labor	Kerosene	58	1	90	53
Electrified not so Poor	Some Skill, Capital, Land	Electricity	8	200	3	240

These three summary data set could have been used for the rough estimation of the three unknown model parameters a, b and c when the price variable is constant and not changing. But the varying quantity of kerosene consumption provides the unique opportunity to use a wider variation in the equivalent electricity price for lighting energy. These kerosene consumption and prices are used to compute the weighted average electricity prices in Table 5-14 and are shown in the brown squares as scatter plots in Figure 5-9. The wider variations in income also plotted as green triangles in Figure 5-7 will provide more data points for a regression modeling of demand as a function of price and income. Other descriptive statistics related to the energy consumption and income profile of about 98 villagers staying permanently in the village out of total 104 households are also shown in Table 5-19.

One can see the widespread use of kerosene from the data. From the 98 data points studied, all of them use kerosene with an average 3 liters per month. Surprising to many will be the fact that all electrified household in the right part of the scatter graph in Figure 5-9 shown as dashes are also users of kerosene even more so than the un-electrified households close to Y axis.

Step 2b: Data Analysis: Derivation of the Derived Demand Model: I ran a regression model with the village data as shown in the scatter diagram below in Figure 5-8. Each data point represents the energy consumption of one family. The X- axis shows the logarithm of electricity demand Qe. The left Y axis represents the price of electricity as well as the consumption of kerosene in liters. The right Y axis represents the income in $/month. Kerosene is used by all except one household that uses SPVs as a backup to the grid. Only four families have incomes above $200 /month as seen in the right axis and on the right upper part of Figure 5-9 with triangle marks.

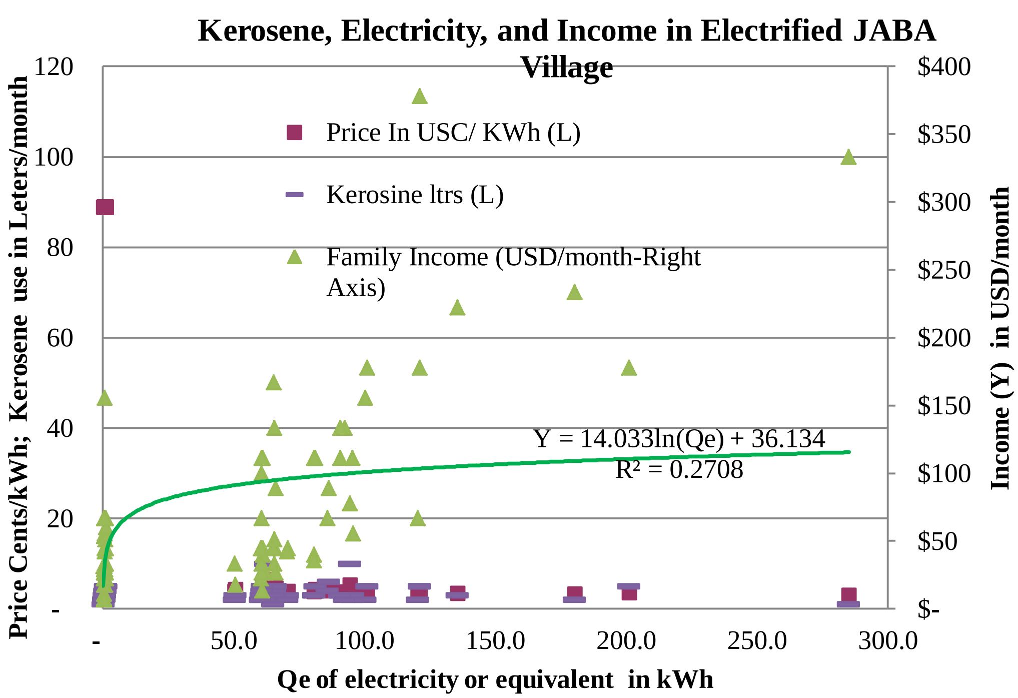

Figure 5-9 Data from the village case study to be used for regression study
Source: Author. Haves (lower and left scatters) and Have-nots (right and upper scatters) in the electrified JABA villages all use kerosene as lighting fuel.

The log-linear demand curve in the project village will be based on the input data shown summarized in Table 5-17.

Table 5-17 Descriptive statistics for the 98 households sampled in the village: energy consumption, prices, and incomes

Description of the Statistics	Kerosene Use liters (L)	Equivalent kWh /month from Kerosene	Electricity (kWh/month)	Electricity (Qe kWh/month)	Weighted Avg Price c/kWh)	Family Income ($/month)
Total for the village	324	81	4,214	4,295	4,468	6,383
Mean	3	1	43	44	46	65
Median	3	1	50	51	6	44
Mode	3	1	-	1	89	44
Stand Dev	1	0	52	52	43	64
Kurtosis	7	7	4	4	(2)	8
Skewness	2	2	2	2	0	3
Range	9	2	285	285	86	371
Minimum	1	0	-	0	3	7
Maximum	10	3	285	285	89	378
Largest(5)	5	1	120	121	89	178

Source: JABA Case Study 2003-8

The result of the regression of this demand with the price, income and consumption correlation is shown in Table 5-18.

Table 5-18 Regression demand results for JABA village

Regression Statistics	
Multiple R	0.993
R Square	0.986
Adjusted R Square	0.985
Standard Error	0.289
Observations	98.000

ANOVA					
	df	SS	MS	F	Significance F
Regression	2	545.684	272.842	3274.903	2.37E-88
Residual	95	7.914	0.083		
Total	97	553.5993			
	Coefficients	Stand Error	t Stat	P-value	Lower 95%
Intercept (a)	4.272	0.065	65.523	7.07E-81	4.142847
Electricity Price c/kWh (b)	-0.0531	0.000	-68.925	6.36E-83	-0.05468
Household Income $/month (c)	0.0033	0.001	6.528	3.24E-09	0.002

Economic significance of the estimated parameters: The use of the semi-log demand function not only helps us estimate the true ability and willingness to pay of the villagers (the true demand curve), but also provides some useful information from the regression parameters a, b, and c shown in Table 5-19.

Table 5-19 Economic significance of parameters of the demand model

	Coefficients	Useful information	Values
Qf intercept at zero price (a)	4.272291	Zero price, zero income demand e^ a	72 kWh
Price parameter (b)	-0.05315	Mark up over marginal cost for a monopoly firm = -1/b	18.8 c/kWh
Income parameter ($/month) (c)	0.003332	Demand rate increase for each $100/month = 100*c	33%

Significance of the parameter "a": The semi-log demand function reflects the very poor village situation with a significant household's average income of about $100 /month. At this subsistence income most households cannot buy appliances even if the electricity is provided for free. The hard limits on appliances purchased also sets the amount of energy consumption. This equation has the interesting property of the limited consumption Qf, when electricity is free (P = 0), derived from the demand $Q = e^{a+bP+cY}$:

$Ln\ Qf = a + c*Y \rightarrow Qf = e^{a+c*Y.}$

$Qf = e^{4.272+.0033Y}$

At P = 0 and Y = 0, $Q = e^a$ is derived from the first intercept parameter; this is the light or electricity consumption of poor households with no income and a zero priced electricity of maximum of 72 kWh/month as the free electricity shown in the last column of Table 5-19 above.

Significance of parameter "b": This parameter is important to calculate the price elasticities of demand at various prices of electricity.

The price elasticity of demand β_p is given by

$$\beta_p = \partial(LnQe)/\partial(LnP) = \partial(LnQe)/\partial(P)*P = b*P \quad (5\text{-}15)$$

The price elasticity of demand, shown in Table 5-20, depends only on the price and the slope parameter b and is independent of income. This gives us the elasticities at the lowest subsidized price of 3 c/kWh as 0.16, at the market clearing price of 31 c/kWh as1.6, and at highest SPV price of 38c/kWh as 2.02. These elasticities become more elastic as price increases. Table 5-20 shows that the budget share even at a low price is high at above 5%, then increases through a price of 20 c/kWh before decreasing to less than 2% at the kerosene price of 90 c/kWh. Thus, kerosene is still used in villages even at its high price because it can be sold in small quantities to meet the flexible cash flow of the very poor. Such flexibility will be replicated by

SPV based lighting in our case study.

Significance of parameter "c": Table 5-20 also shows the income elasticity of demand β_y given by

$$\beta_y = \partial(LnQe)/\partial(LnY) = \partial(LnQe)/\partial(Y)*Y = c*Y \qquad (5\text{-}16)$$

The income elasticity is 0.33 at an income of \$100/month, so if income increases 1% consumption increases by 0.33%, Income elasticity of demand is low at low incomes but rapidly increases with income to 1.67 at an income of \$500 /month. Although a high income of \$500/month is outside the village sample, assuming the same elasticity relation holds, grid power will be preferred by these customers.

Table 5-20 Consumption, income, and price elasticities and the budget share for the very poor in rural India:

Price values in c/kWh: Kerosene 90, grid electricity 62, SPV 38, Pg 20, Pw 10, subsidized price 3; Income values in \$/month: 30, 100.

Regression parameters			**a**	**b**	**c**	**x**
Parameter values			**4.2723**	**-0.0532**	**0.0033**	**Budget share**
Represent ative users	**Income Y**	**Price (Pe)**	**Qe =$e^{4.2723+0.05315Pe+0.00333Y}$**	**Price elasticity Bp = bPe = -0.0532Pe**	**Income elasticity βy = cY = 0.0033*Y**	**= Pe*Qe /100Y**
Very low income	30	90	1	-4.78	0.01 (\$30/month)	2.0%
	30	62	3	-3.33		6.1%
	30	38	11	-2.02		13.3%
	30	20	27	-1.06		18.2%
	30	10	47	-0.53		15.5%
	30	3	68	-0.16		6.8%
Average rural income	100	90	1	-4.78	0.33 (\$100/month) 1.67 (\$500/month)	0.8%
	100	62	4	-3.33		2.3%
	100	38	13	-2.02		5.0%
	100	20	35	-1.06		6.9%
	100	10	59	-0.53		5.9%
	100	3	85	-0.16		2.6%

5.2.4 Step 3: Equilibrium consumption of the SPV supply and demand

Figure 5-10 shows my estimated demand curves for incomes of Y= 50, 100, 200 and \$500/month along with the solar supply price (Ps). With the straight-line SPV supply and a demand curve asymptotic demand to the price axis, equilibriums in SPVs are always assured, as can be seen in Figure 5-8. There is a market clearing solution for each demand line corresponding to any income level starting with the subsistence level of \$50/month. A supply and demand equilibrium is achieved for each demand curve for the solar supply price of Ps = 38 c/kWh. This should not be surprising as subsidized kerosene at 90 c/kWh is still more expensive but the market still clears.

In the next section, I will use the above grid cost and demand information to show how a grid electricity equilibrium does not currently exist in rural India. Nor is it likely to exist in the near future with the average income remaining below $200/month.

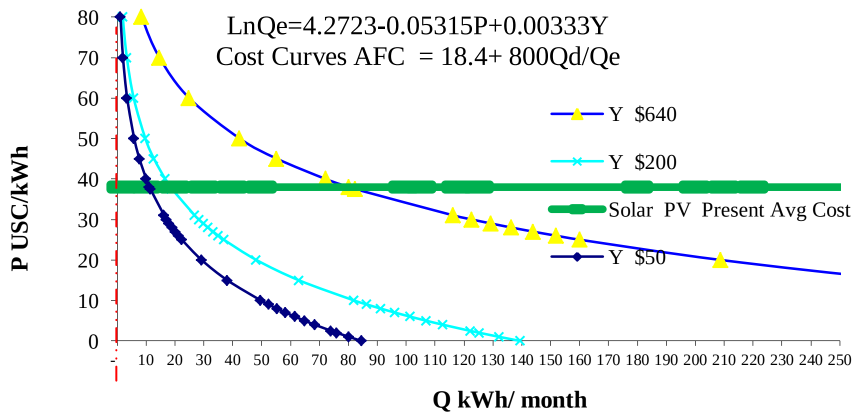

Figure 5-10 Demand curves of JABA village at various income levels Y

5.2.5 Step 4: Equilibrium consumption of the grid supply and demand

The subsidy free level of consumption (Qe) at different levels of income and different grid capacities (Qc) is found where the grid average cost equals the demand price. To find this quantity, set the inverse demand solved from Equation 5-14 equal to LACr from Equation 5-10

$$800Qc/Qe + 18 = 80.4 + 0.0627\ Y - 18.8\text{Ln}\ (Qe)$$

With some rearrangement the equation becomes

$$800Qc/Qe + 18.8\text{Ln}\ (Qe) = 80.4 + 0.0672\ Y$$

This is a transcendental equation with no solution for Qe for some combinations of capacity (Qc) and income values. For example, starting with Y =$50/month and Qc = 1/2 kW the demand for electricity has no solution as can be seen from the lowest blue demand curve in the graphics in Figure 5-11, which never crosses the heavier green ADCr curve. I do not find a subsidy free solution until Y = $200/month, where the green hatched demand curve is just tangent to the cost curve. At the targeted 30 kWh shown by the vertical dotted line, Y must be $200, which is slightly less than the subsidy free threshold solution but more than three times the village average family income of about $70/month. Indeed, only 4 households have monthly incomes that exceed $200

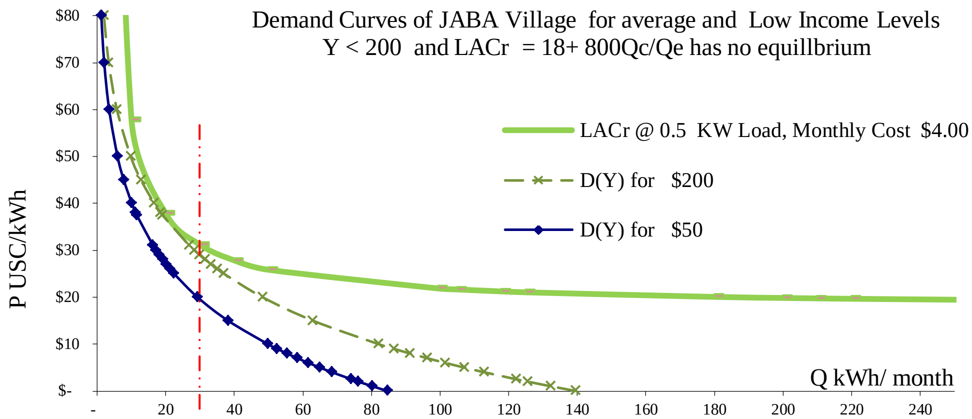

Figure 5-11 Poor and average income customers with no grid equilibrium will need subsidies at all level of consumption.

Thus, we can conclude that there is no grid solution with incomes less than $200, which represent the vast majority of India's rural poor.

Next, we consider a subsidy free solution for the other capacities. In Figure 5-12, we take the cost curve from the 1/2 kW case and add in the costs curves for 1 kW and 2 kW cases. Notice there is no meeting point between the LACr and demand until Y= $400/month for Qc = 1 kW.

For the highest capacity, 2 kW, monthly income must be $600 before the grid becomes subsidy free. This income is outside the range of our village sample, so has not been empirically verified. However, this high income is not a very relevant demand for poor villages in India. Thus, it appears that very few of the households in a typical Indian village have enough income to connect electric heaters and high power appliances to get to such a high level of consumption.

The calculation above shows the answer to Q3 that a low-income equilibrium does not exist for incomes below $200 as the grid cannot be economically delivered below the peak capacity of ½ kW. With an actual income, in the village, of less than $100, the feasible grid market clearing price does not exist at present.

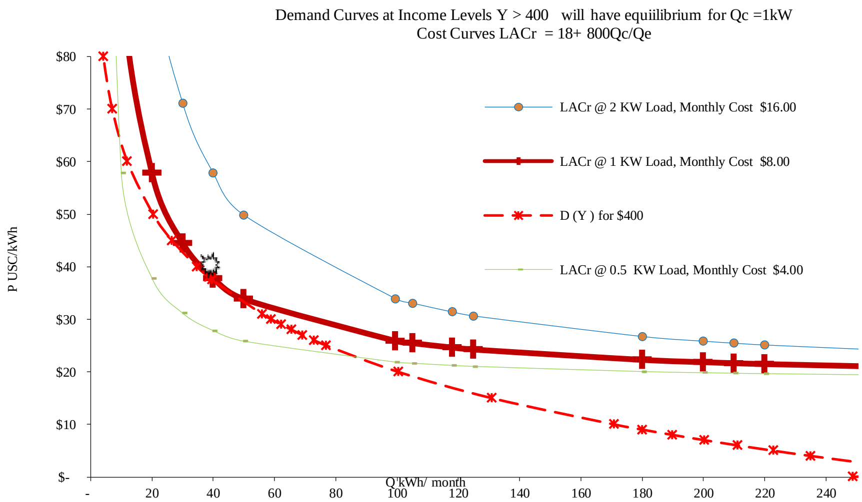

Figure 5-12 Income of $400/month is minimum required for 1 KW grid capacity.

5.3 Q3 - What are the Break-Even Incomes and the Break-Even Electricity Consumption for the Grid to be Cheaper Than Off-grid SPV?

To find the threshold income condition for subsidy free SPVs, I found the income level for the lowest demand that crosses SPVs at as shown in Figure 5-13. The SPV equilibrium output is shown now as an increasing function of income based on the demand equation 5-12.

Ln Qe = 4.2723-0.05315Pe+0.00333Y

For the subsidy-free output, using Pe=Ps =38, Qe= Qs, we get

LnQs= 4.2723-0.05315*38+0.00333Y = 2.256 + 00333Y

The equilibrium quantity from the above equation is given by

$$Qs = e^{2.256 + 0.00333Y} \quad (5\text{-}17)$$

Equation 3-1 verifies there will always be a positive consumption of subsidy free grid electricity, even at zero income. Thus, there is no minimum income threshold issue. When income Y=0, the Qs= $e^{2.256}$ = 9.5 kWh. We can ignore this zero consumption as out of sample prediction of the theoretical semi-log model that was adopted. But we can still consider the observed sample households with very poor incomes of $30-$70/month. Based on Equation 5-17, the subsidy free consumption of SPV electricity for these very poor homes would be 10-12 kWh/month. At the current average village income of $100/month, the projected consumption will be 13 kWh/month. These small quantities of solar electricity can be supplied for efficient appliances at less than $5/month at 38 c/kWh as shown before in Q1.

To find the threshold income for the grid, I use the composite LACr developed in Q1 and the demand curve developed in Q2. I find the demand with the lowest income that crosses LACr at or below Ps. The grid market clearing price exists only for the incomes above Yo= $200/month at Qc of ½ kW load as can be seen from the tangential intersection of the demand line with the composite cost curve of Figure 5-13. This threshold income is twice the current village income of $100/month. The breakeven subsidy-free consumption Qr at this income is 21.2 kWh/month and the price Pr is 36.8 c/kWh.

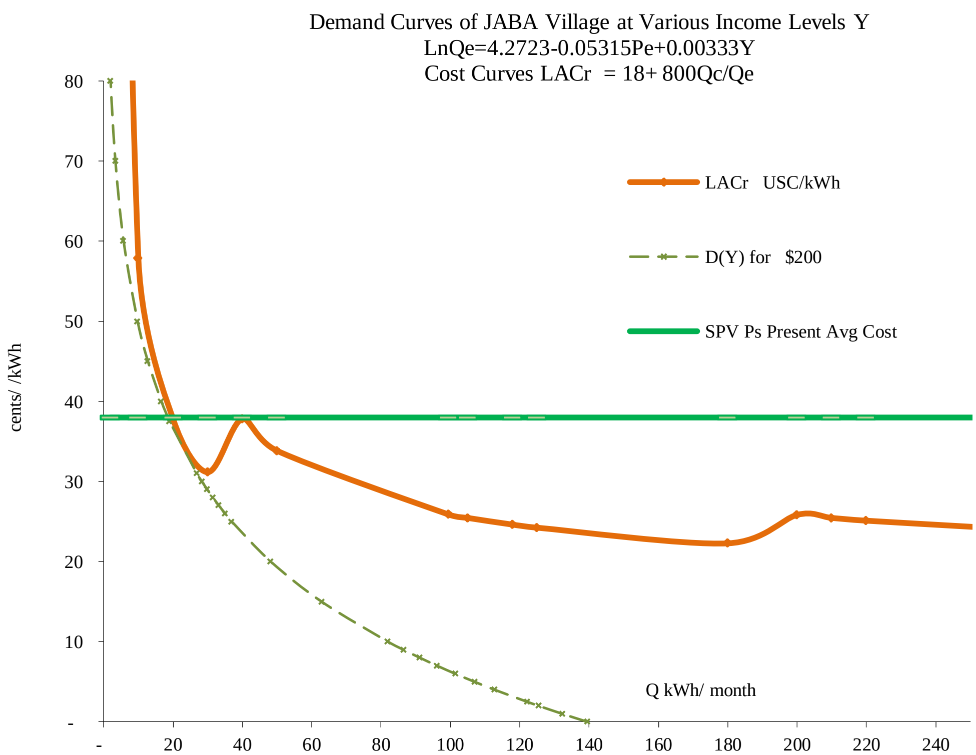

Figure 5-13 Threshold Income and Consumption of Rural Grid to be subsidy free

I find subsidy free electricity for high-income villagers at the market-clearing price is just about one cent below the 38 c/kWh SPV price. The higher the income, the higher will be the consumption and the lower will be the grid price. But such high incomes do not exist now in rural India. Our next question is will income grow enough to make grid electricity subsidy free and cheaper than SPVs in next 10 years up to 2020.

5.4 Q4 - Can Threshold Income and Consumption be Reached to Make Grid Subsidy Free and Competitive with SPVs by 2020?

To look into the future, I must model changes in cost, market demand, and market structure across time. In Q1, I developed the cost of the grid and SPVs. In Q2, I developed demand curves that can be used to model changes in demand as income grows. I use these curves in a dominant firm model as shown in Figure 5-14 assuming SPVs are competitive fringe in order to answer Q4.

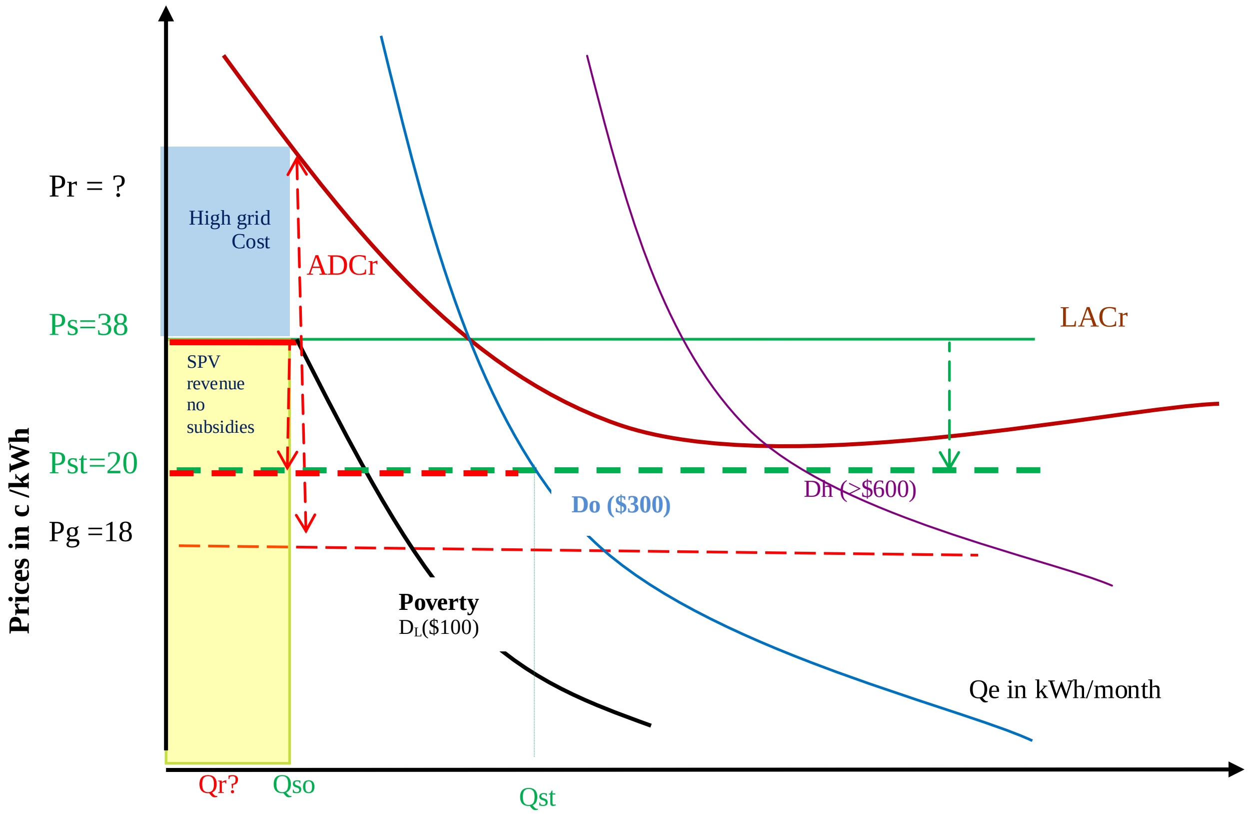

Figure 5-14 Rural Dominant Firm Model

There are three income cases for a dominant rural electric firm as shown in the stylized version in Figure 5-14: D_L D_o, D_h. To get the grid electricity demand for each of these cases, I subtract the rural renewable supplies like SPV electricity from the overall electricity demand for D_L, D_o, and D_h. These residual grid demand curves will be the flat curve just on the green SPV price (shown partly in red) at 38 c/kWh. (SPV elasticity βs is considered infinite with plenty of supply in rural areas).

In this case, for all demands up to Do, the SPVs are dominant, while for all demands to the right of D_o, the grid is dominant. Our challenge then is to determine whether demand will be to the right or left of Do by 2020. In the next sections, I will determine how grid costs, SPV costs, and demands are expected to change between now and 2020. The only situations that can make the grid cheaper than the SPVs is if the income sufficiently increases to move demand Do outward, the grid cost decreases to move LACr sufficiently downward, the SPV price increases to move Ps sufficiently upward, or some sufficient combination of these three effects While the increase in the rural income will be expected, the possibility of grid cost decreasing or the SPV cost increasing is highly unlikely. The possible situations if these three conditions will be fulfilled in future to make the grid cheaper are examined below in three steps. I will first show the current situation with the residual demand curves of grid inadequate to make the grid viable and cheaper than SPVs in a dominant firm model framework. Then I will show how SPV price is likely to fall enough to make grid relatively more expensive even if income is growing,. Lastly, I will show that grid price is only likely to go up, not down.

5.4.1 Step 1: Is the rural grid firm dominant today?

Assumptions and Data

Household Income Y_L= \$100/month

SPV price: Ps = 38 c/kWh

Grid price Pg =18 c/kWh + LACr(Qc, Qr) based on the composite curve

A residual demand curve for the average rural income of \$100/month has been drawn in Figure 5-15. The red line over Ps line is the residual grid demand as SPVs will set the market price at low consumption levels. As can be seen clearly from Figure 5-15 the current grid rural income will be insufficient to create a grid demand supply equilibrium. SPVs will, however, have an equilibrium up to the consumption level of Qs=13.6 kWh /month and P =38 c/kWh. Any further reduction in SPV price will create better market opportunities for solar electricity.

The conventional electricity grid is considered to be dominant while SPVs and other renewables are considered to be in the competitive fringe in urban markets. In these markets, the grid average cost is much lower than the SPV average cost of 38 c/kWh. But the SPVs, at the present market condition can theoretically be a dominant product in poverty prone rural areas with the grid price higher than the SPV price. Any reduction in the SPV price will only strengthen this dominance. I will next move on to the scenario where the SPV price reduction takes place along with the demand increase. A high income will be essential for grid to be subsidy free and cheaper than SPVs. Will that happen by 2020?

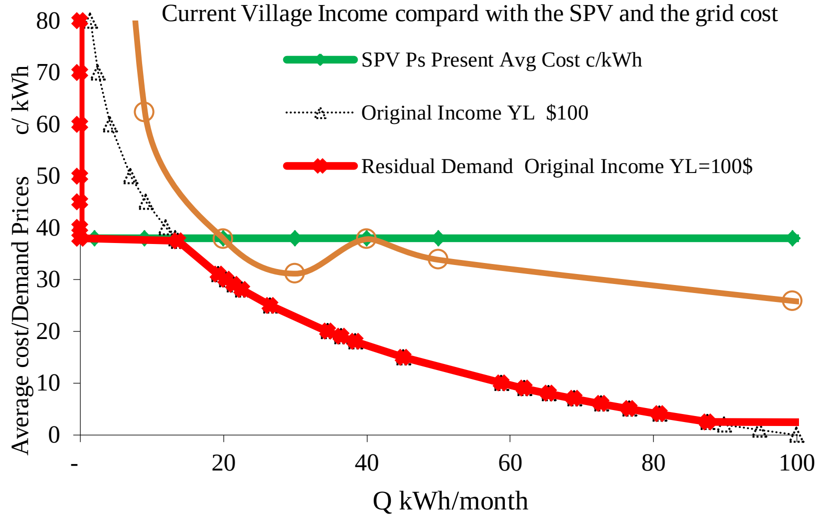

Figure 5-15 Demand increase simultaneously with the SPV cost reduction constraint grid dominance

5.4.2 Step 2: Reducing SPV costs, increasing grid costs, and increasing demand

Assumptions and Data:

SPV price now Pso = 38 c/kWh

Grid cost annual growth = 0%

Income annual growth γ = 10%

Learning rate of SPV (PR, price reduction for double global production) = 10%

Ps will fall due to learning effects and greater consumer acceptance. The predictions of cost reductions in SPVs vary from 15-20% in each doubling of the global production. This is also supported by the learning curve studies done by IEA, World Bank, and the SPV industry.

In our village level dominant model, these renewable price decreases and grid cost increases will be modeled through parameters determined at the global level. The learning curve effects as reported by NREL, IEA, and the Solar Industry Association will be used for the cost reduction of the SPVs.

With a constant annual growth rate of solar penetration, at Ks, the accumulated production Q(t) is by

$$Q(t) = Q(0)*e^{Kr*t} \quad (5\text{-}18)$$

The general form of the experience curve is the power curve as a progress/price ratio in terms of quantity ratio:

$$PR = QR^{-L} \quad (5\text{-}19)$$

Where:

PR = Ps(t)/Ps(0) is the price ratio with an elapsed time t, Ps(t) = average price of SPVs at time t.; Ps(0) = average price of SPVs at time 0.

QR = Q(t)/Q(0, is the cumulative quantity ratio after time t, Q(t) = cumulative production at time t., and Q(0) = cumulative production at t=0.

L is known as the learning coefficient which is the slope of the price-cumulative quantity curve in a log-log scale.

We get the future price from the power curve in Equation 5-19 by substituting QR = Q(t)/Q(0):

$$Ps(t)/Ps(0) = [Q(t)/Q(0)]^{-L} \quad (5\text{-}20)$$

$$Ps(t) = Ps(0)*[Q(t)/Q(0)]^{\mathbf{-L}} \quad (5\text{-}21)$$

Thus, using Equation 5-18 in Equation 5-21, P**s**(t) at time t will follow an experience curve reflecting relation

$$Ps(t) = Ps(0)*e^{-L*Kr*t} \quad (5\text{-}22)$$

which can be expressed in terms of the exponential reduction in price with annual escalation rate of α (a negative number for future price reduction) as,

$$Ps(t) = Pso*e^{\alpha*t}$$

Or, $\alpha = -L*Ks$

L has a special meaning as can be seen by taking natural log of Equation 5-19, we get

$$Ln\ PR = -\ L*Ln\ QR \quad (5\text{-}23)$$

L = - Ln PR/Ln QR. The general practice in the industry is to express PR in terms of doubling of the production capacities, QR=2, so the price ratio becomes from Equation, 5-19

$$PR = \mathbf{2^{-L}} \quad (5\text{-}24)$$

Thus the learning coefficient determines the progress ratio, which for the SPVs over the last few years has been around 20% with an L value of 0.332.

From, $Ps(t) = Ps(0)*e^{-L*Ks*t} = Ps(0)*e^{-L*Ks*t}$ which can be expressed in terms of the exponential reduction

$$\alpha = -L*Ks = -0.332*Ks = -\ 0.332*40\% = -0.129 = 12.9\%$$

I will assume only a 10% progress ratio again to be very conservative with respect to the SPV cost reduction possibilities over the future years. This gives PR= 0.9.

$PR = 2^{-L} = 0.9$; which gives the value of L= 0.152

The SPV cost reduction based on a 10% learning rate (PR = 0.9; L = 0.152) and a 40% annual growth (Photon consulting 2009; IEA 2010a) in the world wide shipment (Ks) is given by

$$\alpha = Ks*L = -0.40*0.152 = 6.1\%$$

Based on the rate of annual income increase γ= 10% and this SPV price reduction at the annual rate of 6.1% as projected above, the equilibrium output is given by,

$$Qs = Qso*e^{\beta t} \quad (5\text{-}25)$$

A household's monthly SPV consumption growth rate is β and is derived from the demand and supply equations as shown below.

If Pet is the levelized cost of electricity from SPV system in time t, and α is the rate of change of the electricity price, then the solar electricity price is given by dPet/dt = α, or $Pet = Peo*e^{(-\alpha t)}$. If γ is the rate of growth of households monthly income Yt, then:

$$Yt = Y\,o*e^{\gamma\, t}$$

Let Qst be the quantity of SPV used Qet when Pet= Pst. Using Pet in the household electricity demand Equation 5-13, we get

$$Qet = e^{a+bPet+cYt} \text{ or,}$$

$$Qst = e^{a+bPst+cYt}$$

$$Ln\,(Qst) = a + b*Pst + c*Yt \quad (5\text{-}26)$$

The rate of change of Qst can be given by β = dQst/Qst*dt = d(Ln Qst)/dt.

Differentiating Equation5-26, we get

$$\beta = d(Ln\,Qst)/dt = b*dPst/dt + c*dYt/dt$$

$$= -b\,\alpha\,Pso + c\,\gamma\,Yo$$

$$Qst= Qso*e^{(-b\,\alpha\,Pso\,+\,c\,\gamma\,Yo)t} = Qso*e^{\beta t}$$

With b = - 0.05315, α = -6.1%, Pso = 38 c/kWh, c = 0.00333, γ = 10% (assumed growth rate in rural India from the present Yo = 100 $/month)

$$\beta = -\,0.05315*-0.061*38 + 0.00333*0.1*100 = 0.156 = 15.6\%$$

Subsequent years of SPV consumption will be given by

$$Qst = Qso*e^{\beta t} = Qso*e^{0.156t} \quad (5\text{-}27)$$

At the projected annual 10% growth rate, income by 2020 could be as high as $300 per household, which could allow demand growth for the grid with constant SPV price. Figure 5-16 shows the income growth Yt and equilibrium SPV supply Qst from Equation 5-27.

The dominant firm model introduced in Figure 5-13 is redrawn with the new income and new prices in 2020 in Figure 5-17. The grid cost at ½ kW peak load is then expected to be subsidy-free at the high income of $300. However, SPV price will likely have fallen about 50% by 2020 as shown in the dashed green Ps= 19 c/kWh line in Figure 5-17. The residual demand line for the grid will be the new solid red line at higher income Yh=$300 as shown in the Figure. The cost of the grid will then be clearly higher as seen from the composite LACr line (shown in brown) even at ½ kW load peak, which is clearly above the red residual grid demand line. With higher demand for electricity at $300 monthly income, peak capacity demand will most likely increase to the 1 kW. When 1/2 kW line is not competitive with SPVs, it is hard to argue that

1kW capacity will be competitive. This is also seen from the fact that the composite LACr curve is well above the lower red residual grid demand line for both ½ kW and 1 kW sections.

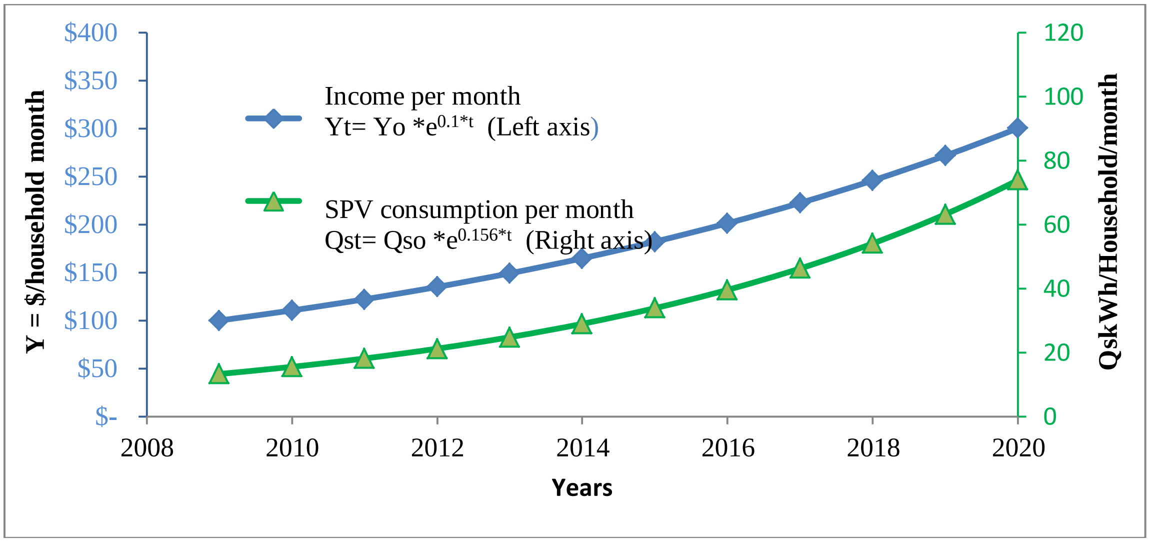

Figure 5-16 Effect of household income growth on SPV consumption

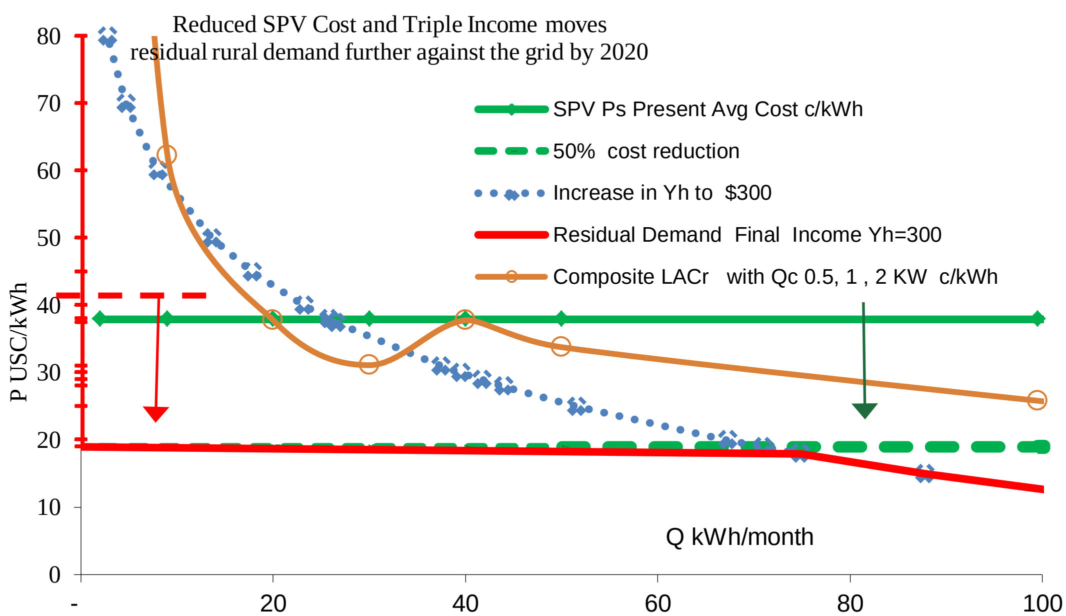

Figure 5-17 Demand increase simultaneously with the SPV cost reduction

Thus, the grid is not likely to be a dominant player in the rural market without subsidies. Just with the two cents reduction in the SPV price from the current 38 c/kWh, SPVs remain the cost effective dominant rural electrical energy instead of the grid electricity for the vast majority of the rural population not yet electrified. SPVs will remain dominant for the entire forecast period up to 2020 with the most likely price reduction. As this condition of SPVs as dominant was inferred from the discussion above when the grid price is not increasing, there is no need of doing the similar graphic analysis for when the grid is increasing. SPVs will obviously be the least cost option.

5.4.3 The unsustainable dominant grid firm when SPVs have lower price risk and non-cost advantages

According to the Cambridge Energy Research Associates (2008) Power Capital Cost Index, the cost of new power plant construction has increased 130% during the past eight years with almost 70% of the increase occurring since 2005. The demand for material in China and India and other supply constraints and increasing labor costs are the key factors for these cost increases. Even the O&M costs are increasing at a rapid rate in Indian utilities. The assumed O&M in our case is only 5% of gross fixed assets where both the urban (Delhi) and rural areas (Orissa) in India charge 15-50% of their gross fixed assets as operating and maintenance, employee, and repair and material costs (DERC 2007-2009/OERC 2009). The various conservative estimates in favor of the grid can be seen in Table 5-21. The mere 7 c/kWh benefit that we saw for ½ kW capacity might just be the result of such conservative estimates. When all the costs are factored in (higher actual electrical T&D losses of 45%, longer lines and higher grid costs of 2008, pollution related costs, O&M costs of above 5%, cost related to high 30kWh/month consumption) the grid costs will be much higher. A recent study for the USA by CERA (2008), McNerney et al. (2010), and (NARUC 2009) also suggest there will be no reduction in the fossil-grid costs and the cancellation of many coal plants attest to the risks of cost escalation. The SPVs might already have achieved grid parity in rural India. Even the government of India itself wants to see the SPV electricity price to reach grid parity at the retail level by 2020 and to be at par with the cost of base load coal plants in 2030 under its new solar mission announced in early 2010. It is therefore not clear why another agency of the same government encourages the rural grid promotion through RGGVY. The mechanism to deliver electricity through the rural grid may have been a twentieth century compulsion, but may no longer be a necessity, if the true economic costs, demands, technologies, and market dynamics of rural electricity consumption are considered in this century. When the grid has above cost risks, off-grid SPVs in contrast have many additional externality benefits that make SPVs even more desirable in both cost and non-cost terms. I will summarize briefly the lower market price risks and externality benefits of SPVs that will accelerate the loss of market dominance of the grid here in a competitive market.

The modern ICET and service industries do not require a lot of electricity, and rural areas are not ready to use electricity for large-scale manufacturing and to harness the grid scale economies. Modern electronic gadgets and lighting can not only transform villages, but they are also becoming more and more energy efficient to be easily powered by SPVs. Fortunately, the cost reduction of SPV technology is not dependent on rural demand but the global learning curve effect of the SPVs; price reduction is based on global production and consumption, learning by doing, learning by using, and the enormous innovation in this technology going on now the world. Global solar consumers have driven down the price of SPVs for the benefit of the rural poor. If the market clears today, it will be more competitive and vibrant in the future based on the usual prediction of the traditional dominant firm model.

Almost all the negative externalities of the grid discussed earlier in the literature review are avoided in a competitive market where the price reflects all internal and external costs. I have considered the emission cost in my costs comparison and showed that SPVs are of same cost as rural grid based on a conservative estimate. Let us consider other costs such as adverse selection, moral hazards, elite capture, regulatory mistakes SPVs provide a platform to build a competitive market when there will be no barriers to entry. The grid-related adverse selection problem is non-existent with decentralized household or community owned energy systems. Metering and information asymmetry will not exist in a competitive SPV market, when promotion of the off-grid systems can be properly designed, well targeted, and administered. Elite capture and moral hazard are also prominent in ill governed societies. Off-grid renewables will be free from such issues with no monopoly and regulation. Lack of customer choice to shop around for alternative suppliers is the root cause of these problems. The off-grid solar industry can remain free from such single supply regulated monopolies and can easily provide multiple energy options and customer choices. The small scale, portable, low maintenance, and self-serviceable SPVs are very valuable for many off-grid applications and there is less potential to free ride or pass the costs to others as in a socialized grid business through a defective regulatory process. These attractive features will be to the disadvantage of the grid, which will lose further market share and scale economies.

Recently terrorist threats and cyber-attacks are at the top of electric grid operators concerns. Terrorists can attack the production facilities, the hydro dams in the high isolated mountains, the unprotected gas and oil pipelines, nuclear sites, or large transmission systems of a grid system. These attacks can be avoided or countered through decentralized energy systems at the load centers that are so dispersed and isolated from each other that no central event can destroy them. Decentralized off-grid SPVs are safe and the loss of one SPV system does not create wide spread failure. Wide spread failure is a consequence of the loss of centralized nuclear, hydro, or coal plants due to catastrophic natural and human-made disasters such as earthquakes, storms, floods and terrorist attacks. Most Indian villages were isolated and their culture has remained intact after thousands of years of external aggressions, even though large cities, temples, and monuments have been damaged. The renewable off grid system will bring another level of security to Indian villages and to the country as a whole. We can see that they are too small and too many to be attacked by human aggression or completely lost in natural calamities. Another advantage of solar and biomass electricity is that they are adequately available in almost all parts of rural India. It can diversify the rural energy supply, delink rural economies from the fossil-grid disruptions and guarantee that a civilization that has lasted many thousands of years does not fall for lack of adequate modern energy. Rural users can lower their own costs through learning to SPV systems while also bringing down the cost of the fossil system in urban use. In addition, the enormous foreign exchange outgo can be avoided through fuel import substitution, local energy harvesting, by creating jobs, and local skills in new technologies based on renewable energy.

These advantages are not easily factored into the cost, demand, and market prices. However, they make SPV electricity even more attractive suggesting that rural households will in the long term be better off deriving their own energy from their own backyards or rooftops. The biggest advantage of off-grid SPVs is their ability to create competitive electricity markets not only for poor Indian villages but also to bring efficiency to urban electricity markets in India that I will discuss next. I will suggest how the subsidies can be reduced, diverted or replaced to create more equitable resource allocation and a competitive market for off-grid SPVs. This will further support my arguments to let villages develop less expensively through off-grid renewables and let cities buy time to continue in the fossil-grid model for their ultimate transition to a renewable-grid in the next section.

5.5 Summary and Policy Recommendations Based on Cost and Demand Studies

The integrated demand and supply analysis of the grid and SPVs showed that grid is cheaper only if the rural grid can be supplied at ½ kW peak load and the inefficient appliances are used by the poor villagers. Under more efficient use or higher peak demand rural grid is inferior to solar electricity. Again, under no circumstances, can the rural grid supply be subsidy-free with the low current demand at the villagers' average income below $100/month. A "dominant firm" model was used to assess the economic feasibility of the grid in rural areas by 2020. The demand model showed that the rural grid's demand is very low and the grid average cost is very high.

Thus, an unstable monopoly is surviving with unsustainable subsidies. Such low demand in rural areas might be the result of the large use of free and cheaper biomass, biogas, and solar thermal energy relatively easily accessed by the low-income rural consumers that will continue in future. In a dynamic framework using learning curves, I showed that even a costly renewable like SPV electricity can compete with the rural grid, economically meet the rural demand, reduce the needs for rural energy subsidies, and enable private or community organizations to deliver energy services in competitive markets.

An objective of this chapter has been to search for a solution that would reverse the existing emphasis on electricity subsidies and provide clean energy to the rural poor through competitive markets more efficiently. The SPV alternatives could reduce the long-term subsidy, increase competition with the grid, and increase the personal responsibility of the owners in operating and maintaining the systems at optimal conditions.

However, since consumers do not see the true costs, they may not move to this cheaper energy option. My first recommendation, then, is to remove grid and kerosene subsidies. At the same time negative externalities should be internalized in prices so customers see the true costs of their purchases. Removing these important barriers to entry is essential before a competitive SPV market can develop.

My cost study also indicated that the urban grid is feasible. Electricity has a high value in urban areas where health, education, and production opportunities are more prevalent. Urban customers already pay a high cost for electricity and their incomes are now above the $200/month threshold income I computed for rural areas (Shukla 2008). At the same time, the threshold income for subsidy free urban supply is also lower as the cost of urban grid supply is lower for the following reasons: fixed investment costs are lower, they can be shared with high load factor businesses and richer customers, while O&M and electrical losses are also lower. The recommendation from these observations is that the urban and rural grid should be unbundled with the rural grid no longer draining off cross-subsidies.

Modern communication technologies and modular, affordable electrical devices powered by SPVs are important to join communities together irrespective of distances, and allow people a higher quality of life. Until their incomes, skills, and trading abilities are significantly increased, the rural poor can self-provide most of their daily electricity needs through their own efforts without waiting for external subsidies. It might be possible, however, that, by the time they are skilled and have a high enough income, SPVs will no longer be a fringe technology but will enter the mainstream rural energy market. The cost and price information developed in this chapter helps point the way to such a cleaner and more sustainable rural world.

Table 5-21 The comparison of the restrictive assumptions in favor of grid verses actual observed values

		Grid			**SPV**		
	Parameters	Assumed	Actual range	Source	Assumed	Actual range	Source
Costs	**Wholesale market**						
1	Marginal energy cost	12 c/kWh	12-18 c/kWh	CERC (2009)	Not Applicable	NA	
2	Transmission/sub trans Cost	0	1-2 c/kWh	CERC/OERC (2009)	Not Applicable	NA	
3	Emission Tax/costs	0	3-8 c/kWh	PACE (2005)	Not Applicable	NA	
	Distribution Market						
4	**Capital Cost $/kW**	**460**	**500-1500**	**RGGVY 2005/2008**	**4500**	**2200- 4000**	Local market/CERC (2008-09)
5	Capital recovery factor	14.50%	based on 14% cost of capital and 25 years life	CERC//OERC 2009		based on 14% cost of capital and 25 years life	
6	Discount factor	14%	5-12%	real factor not used @5% SPV break even			
7	O&M Cost	5% of capital costs escalated @ 5%	5% only for repair an material R&M 15-43% @ 3% -7% for O&M costs	CERC/DERC/OERC (2007-2009)	0.5% @ 5% per year	0.5% @ 5.74% per year	CERC 2009
8	Generation/CUF	30 kWh/month for 1/2 kW load	9-70 kWh/m (4-12%)	IEP (2009) Dubash/Gablers (2007-9)	5 sun hours/day	4-7 sun hours	MNRE/CERC/Merdrich
9	Rural LV Distribution Loss	35%	45-95% (LV average- Rural)	OERC (2009)	No loss		
10	Cost of funds	14%	Tax rebate, government procurement, guaranteed revenue, subsidized loan reduces the costs RGGVY, MOP, CERC		14%	No such guarantee/tax break exists	
Demand							
11	Income in $/month and growth rates	100 growing at 10%	80-90$/month NCAER past growth rate has been only less than 10%. Rural growth rate is much less 4-6%.				
12	Capacity demand	½ kW for 80 customers and 1 kW for 40 customers	Installed capacities per customer will be high in most situations as enough customer will not sign up for first 5-20 years (JABA case study and others		Any short term capacity needs 0-2 kW can be met through suitable battery design, as there is no grid connection, there Is no fear of grid overuse		

CHAPTER – 6 LESSONS LEARNED AND IMPLICATION OF STUDY

The cost study in Chapter 5 quantitatively showed that off-grid SPV is the cheapest option for the rural poor. In addition, other non-quantified beneficial externalities make SPVs even more favored. So if the SPV is so obviously the electricity option of choice, why is this option not being phased-in in rural India or in other poverty ridden parts of the world? The following implementation issues for SPV electricity learned from the JABA village experiment will shed some light on this issue

6.1 Phase I: Energy-only Solution for Light, Lifestyle Comfort for Rural Poor

In Phase 1 of my case study, which only sought to bring light, I found that the rural poor are not seeking large water pumps or climate controlled homes. What they need are food, water, sanitation, transportation, infrastructure, a comfortable home, and opportunities for community entertainment and production. Many of these needs can be powered by muscles and local renewable energy supplemented by SPV electricity. A solar PV system can be bought from the market and maintained by the villagers. A long lasting 80 W SPV panel can be loaned or leased at a total cost of less than $320 to an average family with monthly income of $100 for powering lights, a fan and a TV. The family can payback the initial capital cost of the panels at less than $5 per month for 6 years at zero discount rate. If a 14% interest rate is assumed the investment can be very easily recovered in a few more years, much before the end of the 25 years of useful life. The household might be asked to buy its own battery system to fill energy needs at night inside homes and portable power supply outside homes. All the village households do not need an 80 W solar panel at the same time. Only 10 W systems are needed for lighting and cell phone charging at the individual family level for the poor with monthly income below $60. They can pay off this cost at less than $2 per month as they pay the cell phone company. Even the very poor with a family income of about $30/month can use a 2 W solar LED light for their bare minimum evening light with much better quality than from a kerosene light and pay for it at less than a dollar a month. A larger solar PV system can be installed in the village community center to meet the needs of a cluster of such poor families. The more advanced 40 W and 80 W SPV panels may be added as villagers learn and improve their skill and production capabilities.

About 10 kWh/month of very efficient SPV electricity can be supplied to each of the un-electrified or poorly electrified 80 million rural households at an upfront cost of $25.6 billion

(80W*$4/W*80million) over a period of 5-10 years. This is more than the $13 billion proposed by the RGGVY for the rural grid but involves no recurrent costs for inefficient use of energy, distribution system, related subsidies, losses, and other structural issues of the grid monopoly and elite capture. Recurring O&M, routine metering inspections, and legal actions would not be required. Solar water pumps, bright LEDs and CFLs, and solar powered fans and refrigerators could be procured for greener and more value added services compared to what is possible through kerosene and the electric grid. This would have been economically more efficient and socially more equitable with everyone getting the same amount of government subsidy. Those who want more services could get them from the market place. Rural energy consumption could be disassociated from the cross subsidies of an urban market.

6.1.1 Opportunities to counter the energy divide and elite capture in JABA village

The very distinct, caste based energy allocation of electricity and kerosene along with possible solar electrification in JABA representing a typical village of rural India is shown in Figure 6-1. The area graph shows the darker side of the fossil-grid with the larger dark area representing the electricity deprivation in the village to the lower caste groups. This one graph shows many aspects of an Indian village, such as the energy divide with elite capture (left upper class with more electricity) and the right lower classes that survive on kerosene. Also shown are subsidy lock-in (both electricity and kerosene are subsidized) and the challenges for subsidy free solar electrification in JABA village that could very well be applicable for other rural villages.

The figure also shows the possible opportunities for SPVs. All villagers can be provided some solar electricity based on their paying capabilities. The stacked bars in the figure show this potential level of solar energy penetration in JABA village with 5% of each household's income allocated to the superior SPV lighting or home systems. The larger 40W/80W solar home systems, which can be provided subsidy free for average income homes, are shown in the bottom green bars with white dots. The smaller 10W solar lanterns for less than average income families are shown in the middle diamond patterned bars, and the very cheap rechargeable LED/CFL lanterns for the very poor are shown in the top light green bars. These small systems can be powered by 1-3W SPVs even during cloudy days, through hand cranking, or they can be charged in a village charge shop with daily/monthly rentals. No subsidy, no elite capture, no metering and no inspection are involved in providing such an equitable lighting solution for the village. However, the actual result, I saw in the village is an eye opener that led me to significantly change my perception and understanding of energy intervention for the rural poor in India. The case study for bringing light to poor homes failed because of the many short-term glitches in the

SPV products and the social practices of the villagers. Similarly, a competitive market for household lighting also came to a halt as subsidies to fossil fuels and the grid discouraged SPV entrepreneurs from entering the potential rural market without similar subsidies. These short term entry barriers and long term structural operating barriers have led me to look for a better energy solution for the village and assess the lack of demand that makes the grid unviable for long time to come.

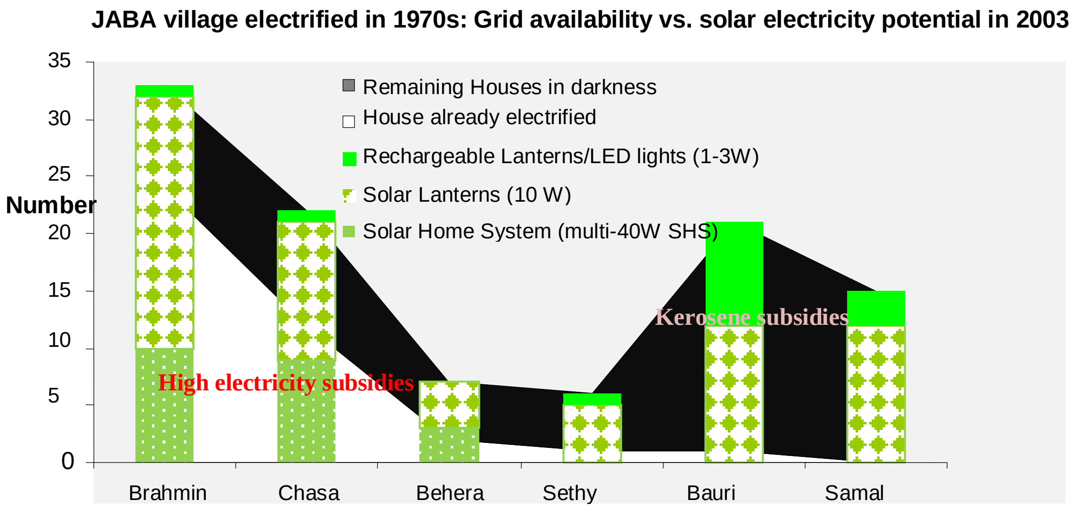

Figure 6-1 Social segregation and energy use: High grid and kerosene subsidies as barriers to entry for off-grid SPVs.

6.1.2 Short term barriers to entry of SPV showed up in Phase I implementation

I started observing many classic socio-economic problems and externalities as possible barriers to entry even during the initial two years of JABA village case study in Phase 1. Most of them might go away with increased learning by doing and using modern energy efficient technologies. These experiences, I believe, could help shape the future strategy in energy delivery to the rural poor. The following lessons learned are also useful for efficient product and process designs for meeting solar electricity markets. They will also have some policy implications on access to solar radiation and social infrastructure for the poor at the least and affordable costs.

1. <u>Externalities:</u> Lack of adequate sunlight due to shadow of nearby trees on many poor households was a handicap that needed close scrutiny of SPV projects. Some households had to return the lanterns, as they did not have enough solar radiation during winter months as their neighbor’s trees shaded their property. The expensive solar panels for their lights should not have been offered to these households in the first place. Centrally charged rechargeable

lanterns should be adequate for their needs. The fact that partial shade can shut off solar generation or reduce it to about 10% of full capacity was not understood fully by the users. The possibility of carrying the solar light to the work place and charging it there could not be popularized by the project team because of the unwillingness of volunteers and the lack of any great interest by the beneficiaries to continue the awkward process. These shading issues for the poor are more of a problem for the landless labor class who are crowded in a small area. The more shade insensitive thin film SPVs could solve some of these problems in the future, but for the moment the government would need to step in to solve the solar access issue as in Wisconsin where no household can legally restrict the reasonable solar access of a neighbor. If it is unreasonable to cut a tree that might otherwise provide shade and keep a house cooler, participants may come to a Coasian bargaining solution. The panel may be mounted higher up on a platform at additional costs. Or a party could contract with a neighbor to rent the solar panel and provide a micro-grid power supply for two to four customers in the shaded zone. Another alternative is to have a community charge shop as described by Khandepal and Chouery (2009) where the poor will pay some fee for battery charging for all lighting and ICET devices. Theft, vandalism maintenance, and security/insurance issues will then be moot for the poor households. These are the experiments village users and entrepreneurs can search for, as argued by Easterly (2006). Such searchers may be able to use small modular off-grid systems that planners from national and international development agencies cannot. In that respect the SPV high cost argument often becomes invalid for the technological and market dynamism it provides in rural areas.

2. Free Riders: Another family found that sharing the 1.5-dollar monthly costs amongst families living very closely becomes cumbersome with a free rider problem. The person who contracted with the project team had to pay for the entire cost while others in the vicinity had a free ride on the solar light. If the same customer had purchased kerosene every day, she would have had the leeway not to buy every day and could have forced the others to buy kerosene part of the time. After a solar lantern was provided, the neighbors saved money on kerosene but did not share the cost of the solar lantern. This interesting spillover effect taught us an important lesson. We provided solar street or community lights powerful enough for children to study under in good weather at night and for adults to assemble for evening entertainment and enjoy the modern reliable solar technology at work. For such community use, a subsidy is necessary but the light gives positive externality benefits to all. Some innovative entrepreneurial solution will be required to deal with joint family and communal

use. Non-divisibility: Some houses with more than 2 rooms needed more than one solar light but were not willing to pay double as their kerosene payment was much less than 3 dollar per month. Probably one solar light and one back up kerosene lamp would have been a better solution. But the consumer did not want to experiment as he felt it too risky an investment. During the initial phase, LED light was not very popular due to poor lumen/Watt and frequent battery charging with the lower efficiency of LEDs compared to CFL. Now it is possible to provide two LED lights (one high-powered 3W and another low powered 1W) at the same cost as for one solar powered CFL lantern in 2003-05.

3. Lack of aspiration: The village community has been subject to centuries of isolation and deprivation from material enjoyment. They do not aspire to the comfort and opportunity benefits of modern electrical systems. This lack of aspiration is partly driven by the fact that they lack information, income and opportunity to procure the modern electrical devices. Some households did not see any great value for an electric light, as they did not have anything to do at night. They were uneducated with no children in school. After a day's work, they went for community programs or rested and preferred to spend their money for clothes, food and medicine.

4. Lack of incomes: Most of my customers were paying by exchanging labor and were satisfied with the product. By allowing poor households to work for their payments, I was able to provide them with light even with their low incomes and the lack of a capital market in the village. The collection of cash dues from the poor with their many competing mandatory health and social expenses remained a great challenge. Though no one has sold a solar lantern borrowed from us, it came to our notice that many have sold their cows, land, and rice stocks to pay for a son's medical costs, a daughter's marriage or for other social obligations. Social security and critical medical care programs from the government as in developed nations could solve some of these issues. The variable monthly income stream of the poor affects their ability to pay and any persistent pressure often led to the return of the lanterns. So far as we could allow them to pay with labor, payment was not a problem. Although there has not been a single buyer who was willing to pay for the lantern up-front, there has been no default in payment by shop owners.

5. Skill and complementary factor shortages: The solar charging of radios, fans, computers and mobile phones was theoretically possible, but there was not enough local capacity to provide training, minor operating and design adjustments in the pins, switches, outlets and

connectors, and maintenance services. In a holistic approach, we need capacity building of local entrepreneurs as well as the complementary skill based technical training for applying renewable energy to rural applications.

6. Non-competitive device suppliers: The existing suppliers were all located in the state capital catering to the government programs and had no incentives to be customer friendly. Even the most reputable manufacturer took a long time to rectify a common switching problem of lanterns that we faced frequently. Quality problems of solar systems in the local rural market made them less lucrative than in the hot markets in developed nations led by Germany and the USA. The demand driven price increase and the silicon shortage in 2005-07 brought solar investment to standstill, and we had to wait until 2008 for the next round of price decreases. To gain reputation and consumer confidence, local manufacturing, modern customer management systems, and more training centers will be required to change the perception of solar devices as unserviceable.

Phase I of the case study research was to bring light to promote future sustainable development. Such a rudimentary Alternative Development Initiative with Renewable energy and Energy efficiency (ADI-RE) that I introduced for household lighting, however, failed to be self-sustainable as the small savings from solar light could easily be wiped out by health costs or other social obligations There were also many other initial problems of new technology dissemination that perhaps could have been solved with enough effort. But the big government subsidy to fossil-grid competitors could not be addressed by the project team. I address this long-term structural barrier that will discourage market for off-grid SPVs in the next section.

6.1.3 Long-term structural challenges observed in Phase I energy-only initiative:

As described above, introduction of off-grid SPVs in rural India require some promotional efforts to transfer skill as well as micro financing to let the rural poor learn by doing. But there are certain structural issues that need government attention. Theoretically, demand and supply for SPVs match and will continue to do so in the future. However, that is not enough for the SPVs to make a dent in rural India without addressing the core issue of anti-competitive subsidies to kerosene and the grid. On the contrary, the government continues to subsidize the inefficient grid and kerosene, while these same ration shops with additional private market entrepreneurs could instead create more supply channels to sell SPVs and efficient electric devices. Not only energy subsidies, but also food, fertilizer, agricultural loans and housing all are provided at subsidized rates to villagers without expectations of returns to the costs. The total subsidy value constitutes a significant part of the villagers' incomes that are not transacted at market rates. Thus, the lack of a market and proper price signals are perennial problems in the rural economy. Thus, selling SPVs in rural homes at their true cost is infeasible.

A grant of one solar light to each un-electrified rural household through the kerosene distribution channel of government controlled ration shops would have diverted kerosene subsidies to the solar devices, nullified the anti-competitive nature of the kerosene subsidies, and the transaction costs of small payments. But our small project team has no resources to change a mammoth government bureaucracy. Many government announcements to reduce the kerosene subsidies and provide funds for solar lanterns during this ADI-RE project implementation (2004-2009) in JABA (including the very top, competition-friendly, current prime minister) were made, but no action has been taken.

Rural households are different and their needs varied widely based on their income, family size, occupation, skill, lifestyle and other preferences. Not all of them are searching for easy subsidies and many try to experiment with new technologies and to develop skills so that they can be financially independent. Despite the subsidy barrier, the story of Babaji Bhoi, a labor turned semi-skilled mason will be useful here. His example will also show subsidies can not only reduce the demand for clean and competitive solar systems but also lower the demand for the poor quality of grid to the extent of making it completely uneconomical.

Babaji rented a solar lantern 5 years ago from the project and was the first beneficiary to have paid off all his dues, even after electrifying his home with subsidized grid electricity three years back. He values his little solar system that could power a light, radio, and cell phone. His school-going children experimented with LEDs and an SPV panel while saving energy from the grid. His electricity bill averages 9-12 kWh/month and he pays just about a dollar to the grid company for this electricity. He does not pay anything for the lantern as it is free for him now after paying one and half dollars each month for 5 years. He gets reliable solar electricity for his masonry work, his children's education and ICET needs, and his wife's work in the cow shed and kitchen garden at night. The subsidized grid could not solve many essential rural activities for which Babaji has come to depend on SPVs. Thus, solar electricity is a credible grid substitutes if a competitive market place emerges on its own. If the government realizes the cost of grid subsidies and removes them, that day could come much sooner.

With adequate perseverance and time to challenge these government subsidies, it could be possible to prove the practical success of the off-grid SPV model. This example explains how the alternative modern SPV systems are not only essential but they also reduce the market size of the grid so it no longer makes any commercial sense. But the government subsidies to the grid still continue as the largest structural barrier to entry of off-grid renewables and energy efficiency.

6.2 Phase II: Developing Sustainable Villages by Phasing in Off-grid SPVs for Meeting Modern Inputs and Outputs:

Bringing electricity to the village either through the grid or by SPV has not shown any significant income impact for JABA households, though it has provided higher amenities and a better quality of life. However, lifestyle alone cannot pay for the costs. SPVs are affordable only if the income impact of these solar devices or some other driver is strong enough.

6.2.1 Observation of an integrated development

When the rural poor, mostly illiterate, have so many competing essential needs such as bringing food to their families, meeting numerous social obligation, surviving from disease, and dealing with catastrophic disasters, it is naive to believe the prediction of a subsidy-free solar solution based on the partial equilibrium demand study presented in chapter 5. This is a great lesson I learned from the case study in the first 2-3 years. It convinced me that a lower cost SPV energy-only solution to rural development is not guaranteed and might very well fail as it has failed for the grid-only solution for the past four decades.

However, I became curious to know how much electricity would be required for developing a new resource efficient sustainable village from the ground up. This led me to extend the research for few more years. For the remainder of the chapter, I will present my observation of the integrated but phased implementation of some of the renewable energy and energy efficiency projects in the village community and production programs.

Despite the commercial failures, Phase I showed the commercial success of portable solar lanterns to provide night light for various purposes including home study, a health camp, shops, and community events. Besides being portable, solar lanterns increase productivity because they provide reliable power anytime anywhere in contrast to the Indian Government's welfare program for the poor providing one incandescent lamp to each family in the village. The same amount of light can be delivered through a much safer and more productive LED/CFL lamp powered from battery SPV systems without subsidies for value-added activities requiring portability, reliability, and flexibility for multiple uses. In Phase II of my village level experiment I osught to provide the four socially relevant outputs that require electricity: health, education, lifestyle, and comfort through energy and various other products and services.

6.2.2 Phase II Principles: Energy for producing more balanced outputs

The perceived primary needs of the villagers were not energy services as such, as they do not have the devices and facilities to use modern ICET. In order to create a positive spillover effect of modern energy, it is necessary for rural communities to get all the HELP services together, as shown in Figure 6-2, as no one of these is sufficient alone. An entire portfolio of health, education, quality of life,/livelihood and production (HELP) services must be provided to develop villages and make them habitable for modern living. All of these can be provided in a phased manner based on the specific needs and abilities of each household and community without requiring huge resources at one time.

The ultimate objective of society is not to provide a few light bulbs to the villagers but to provide them the essential energy services for achieving healthy, comfortable, educated, and productive livelihoods. I will pool together all products and services that provide income under the output called production. Production is necessary for the rural poor to acquire and maintain a good standard of health, education, and lifestyle. Also, a basic purpose in life is to be engaged in productive employment and to be useful to society in some way by producing goods and services.

The costs of conventional health care, education, and large scale production are very high and these services are extremely capital, skill and energy intensive. They can be provided at lower costs in urban areas with high scale economies harnessed by the presence of a large number of high income customers exactly as we saw in the electric grid analysis before. The adoption of these services in rural India with completely different natural endowments of land, labor and resources requires a complete redesign. In the rural production system, the entire output delivery has to be integrated as efficiently as possible.

<u>RE based HELP Activity Summary, Phase II (June 2005 - July 2008)</u>

With an additional $30,000 study investment in the last 5 years, I have not seen the demand for electricity in the village to be higher than what can be obtained from the SPVs for running a middle class Indian home. The community houses, schools, and shops in the village are also no bigger than 2-4 rooms, are less than 1000 square foot, and do not use air conditioning or refrigerators. The only devices they need immediately are light bulbs, fans, TVs and may be a computer and some LED displays which can all be solar powered.

Lesson from the first phase of the case study indicated serious underdevelopment and a need to provide the village with basic social services and infrastructure for modern living. I tried to introduce all these four services together in Phase II, as the ADI-RE-HELP initiative.

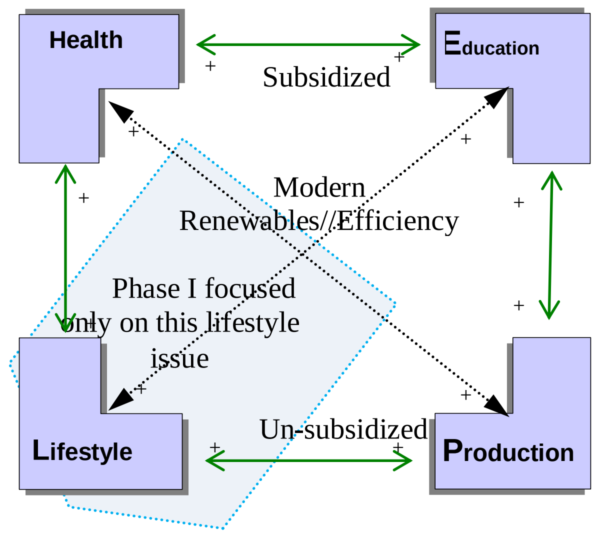

Figure 6-2 Phase II: ADI-RE-HELP expanded from the restricted Phase I using local clean and renewable energy for sustainable community development (most HELP services will use remote electronic services to reduce the transportation costs)

This second phase, introduced in late 2005, took a more holistic approach. I researched energy technologies and their linkages to village production. I considered community energy demand for shared facilities, such as a health center, in overall but phased village development within our limited budget. (For more details of Phase II see Kar and Dahl (2005; 2010)) I also expected quantitative data on productive and community demand for the village. To my surprise, I found that the productive and community demand is not more than household demand. Many of the same solar devices used for average homes are adequate for community, social and productive events in the village.

6.2.3 Barriers to high electricity demand in Phase II implementation: Skill and infrastructure shortages

ADIRE Trust in JABA, an off-shoot of my project to implement the ADI-RE- HELP initiative, is promoting a clean sustainable village cluster around JABA village. But this effort is not without challenges as described below in each of the output sectors.

Social and non-productive sector (health, education, and quality of life) issues: The first lesson learnt by our ADIRE study team in the village from the health initiative is that we need donations and charity to get these services to the poor first before insisting that they use solar lights. When the citizens are so poor that they cannot buy nor can the government provide bed-nets and clean water to prevent malaria, diarrhea, and communicable diseases, how effective is a subsidized rural grid to provide rural health services? Rather, I found that the demand for electricity to provide such basic services as lights, fans, pumps, and ICET for school use can not only be supplied easily with SPV, but they can also be shared with health center projects and be loaned for production or village festivals. This way we can minimize the costs of a separate health center. The portability property of the SPVs is valuable here and increases the capacity utilization factor that the fossil-grid cannot achieve.

Without skilled teachers, teaching gadgets and the skill to operate those gadgets, no grid electricity or solar electricity will change the education services in rural and poor economies. These as yet unavailable complementary skill sets, modern infrastructure such as good roads and broadband internet, and computer maintenance services are essential for attracting education professionals from the urban areas. Where a small road could be completed by our team, broadband services can only be provided by large corporations or the government and it is not expected that this will be available soon. We found poor internet connectivity a critical bottleneck to bringing outside skill and educational material to the village. Computer repair services are also expensive and support services for these high technology devices need to be improved

Lifestyle improvement is required to attract and retain skilled people for further improving the school, health and production services in rural areas. Most of these lifestyle enhancing energy services do not need subsidies, and the poor are willing to pay the services if they see the tangible benefits and have a smooth income without natural or health related calamities. The subsidies are also not required for the community use of off-grid SPVs; they can be a part of the bundled cost of providing community services. Where the community services are provided by the local government, community life could be more comfortable with off-grid SPV as the unreliable grid is not able to provide the same comfort. This knowledge that SPVs can be so useful for community applications, it appears, is not yet widespread and may not exist in the Indian development policy arena.

This implies that if the government, instead of subsidizing the grid and kerosene provides these subsidies to improve the health and education of rural poor communities, the un-electrified communities can pay for part of the costs of the basic electricity services out of their health and education budget. They can also minimize their electricity expenses by taking the minimum required quantity from the market or social entrepreneurs selling SPV products. Individuals, when assured of social security to survive diseases or emergencies and when able to provide much needed education for their children, can also pay for the household energy services. A solar light instead of a kerosene lamp, a smokeless kitchen instead of a biomass or cow dung cake stove can promote a much healthier and safer rural life. Unfortunately the government unintentionally promotes rural disease, darkness, and deprivations simultaneously through kerosene subsidies even to 100% electrified villages to offsetgrid unreliability and non-affordability.

Production bottlenecks: Despite the availability of funding for an electric vehicle for the village productivity growth, we have not been able to develop the confidence and skill within the village community to maintain and operate the vehicle. Although we can provide the SPV electricity, we are still awaiting the availability of a good electric transport vehicle model and after-sales support. It is envisaged that the battery van that we will procure will be charged from the same solar panel that will be used to pump water for agriculture. We were planning to buy two Soleckshaws (solar battery operated rickshaws) which will be used for school children as well as transporting produce from the village to the city market. These much publicized Soleckshaws were supposed to be implemented in Delhi for the Commonwealth Games but were recently abandoned because of poor design, marketing and customer education.

Temporary failures of our community biogas digester used to run the village-café resulted from a shortage of manure and management skill to collect, process, and manage plant operation. Many other production projects such as the brick making plant also initially failed for a lack of skill and management expertise in the early stage. The low level of trust amongst the staff and villagers, early in the project, was tackled by team building projects. Nevertheless, I expect that significant investment will still be required to develop the necessary skills. All these skill building and management activities are not cost free and all villages in India are not endowed with suitable connections to charitable organizations to freely provide these services. Thus, it is essential to develop good rural management practice skills. A solar technician, a plumber, a mason, and three teachers have been exposed to modern manufacturing centers in Auroville, Tamil Nadu and Pondicherry for promoting renewable energy and sustainable building practices in the village since 2005.

6.3 Transition to Phase III in Search of Renewables Based Skill, Capital and Infrastructure

Most of the HELP outputs in the conventional development paradigm are based on dominant fossil-grid technologies. However, Phase II showed us their incompatibility or higher costs for JABA village application. This incompatibility is no different than the case of electricity delivery through the rural grid. A moment of reflection will show that the handicaps of rurality, poverty, and large scale inefficiency that jeopardized the market equilibrium for rural electricity are also responsible for lack of market equilibrium in most of the other output categories. Large scale health services, education, and production activities are difficult to develop in villages and accessing them from cities involves long transportation costs and wasted labor time that the rural poor can hardly afford. All these outputs are subsidized by the government but with no good results as we saw in one example of our core discussion of electricity in the rural grid industry.[15] Such poor implementation in the Indian welfare system is wasteful and not worthy of replication.

I have also been worried about whether the resource transfer from urban donors will continue long enough for our village experimental to be successful. This led me to start Phase III in 2008. My goal has been to quickly develop an unsubsidized model village with a diversified production base for replication elsewhere in India and other rural poor economies.

This alternative rural production model needs to use rurality, poverty, and the efficiency of small scale processes as enablers not handicaps. SPVs can provide the needed electricity for household, community and production without subsidies. Similarly, from my experience of the fund raising activities for the village, I could see the willing support of friends and a growing number of green minded individuals for some amount of capital and skill transfer to direct beneficiaries in the village. Modern internet and Skype/Yahoo services make it possible for individual donors and investors to observe the use of their money. Therefore some initial amount of capital to start a project is not difficult to get. Even doctors and teachers are willing to do remote consulting. Thus some amount of urban skill can also be delivered through the internet as tele-services, where broadband connectivity is available. The subsidy-free delivery of other inputs requires villagers' to not only acquire production skills but also the ability to trade their product and bargain for a reasonable price. One product perhaps the villagers can sell in the future international emission market is their ability to use off-grid renewables and save carbon and pollution and trade them as emission offsets. That is a long term goal of this phase and requires bargaining skills that I myself do not have. But most of the villagers lack even the basic skills of building trust, managing small shops, organizing small companies, or even non-profits to keep proper accounting and to deal with the city based government auditors

Table 6-1 indicates how the much needed but higher skill and energy intensive electric transportation, solar water pumping, and electric power based production activities originally planned for Phase II could not be taken up and had to be deferred to Phase III for lack of appropriate skill and village resistance to new ideas. But from 2008, we have been trying to bring appropriate technical and managerial skills that will be compatible with renewable energy and

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[15] Easterly (2006;2008) and Sen (2005) have brought out interesting insights to the failure of rural educational and health services in a top-down framework. Lal (2006) has shown the failures in the case of farm production and wastage in irrigation water and electricity supply. Jha and Ramaswamy (2010) have recently shown that the food produced in a few states in India and distributed by the federal and state governments to rural poor involves a huge 71% waste in public funding. Poor targeting, elite capture, pilferage and high distribution costs all are well known in any top down model in the Indian welfare system.

energy efficiency (RE) to optimize the use of village land, labor, and conservation habits. I will indicate here the technological opportunities to reduce costs and increase efficiencies of such a sustainable village development phase. I will also indicate how critical is the need of RE based skill and small scale capital, which in turn will require a new set of physical infrastructure such as a local road transport network and high quality global broadband internet. The electric grid, which was earlier thought of as an essential rural infrastructure is off this list, as my JABA experiment has shown me that SPVs can totally replace the rural grid as cell phones have completely replaced rural wired phones in rural India. I have not found much academic literature relating to villages leapfrogging the conventional development paradigm with modern ICET and off-grid renewable energy. In order to trigger a much wider interdisciplinary research in the main line micro economics and sustainable development literature, I will only introduce here the broad concepts that I learned from my case study.

Table 6-1 Renewable energy for lighting, information, cooking, weatherization, transportation to RE-HELP in a phased manner

Renewable Energy for Lighting, Information, Cooking, Weatherization, Transportation				
Phases→	**Phase II**		**Phase III**	
RE →	**Solar PV**	**Biomass - Solar Thermal - Biogas**	**biomass//solar thermal SPV Power**	
Technology→	**Home Lighting//Efficient Electronics (ICET)**	**Clean Heating/Cooking**	**Electric Motors for Pumping/Grinding/ Climate Control**	**Electric Transportation**
Healthy/safe life	LED/CFL below 20W weatherproof evening lights for homes /street	Clean, smokeless stove for food	Clean water, cooling fans, hot water, food storage	Availability of doctors and health workers
Education and lighting	Laptop/TV/LED Projectors/DVD/home lights More time for learning less superstitions and l less closed mindedness		Better health, more time and timely information are enablers for learning	More time for learning, more access to schools, skills, and library
Energy and comfortable lifestyle	Solar lantern/radio /TV/computer based information in homes/community hall for villagers to enjoy.	Solar/biogas save time and create choice for girls /women to enjoy leisure or work	Efficient appliances: fans, pumps, grinders, food processors, broadband internet for entertainment video	Less foot travel but more healthy, nightly, summer work in local farms/shops
Production, well-being	Production ideas given, Access to market, and flow of information improved	More time for production with lighting and micro irrigation supply	Tube-wells//pumps bricks, hand pumps, organic farming	Access to inputs, markets, finance, skills, and entertainers

6.3.1 Technological opportunities of sustainable rural development

Phase III of the village development postulated that the urban factors such as modern renewable energy and efficiency (RE) based skill (S) and micro finance to buy RE devices and efficient capital goods (K) along with the modern rural infrastructure (I) of roads and broadband internet are essential to make the land (L_1) and labor (L_2) of rural areas more productive and a source of income. Taken together these five inputs are denoted here as SKILL. This select set of RE based urban skill and capital with the rural factors land and labor can form a compatible set of factor inputs RE-SKILL for subsidy-free renewable energy based development. This is an improvement over the previous Phase II (ADI-RE-HELP) initiative. In the earlier initiative, all the outputs including high paying skill and capital were sourced from urban areas, where they are currently available with no focus on their possible development in rural areas.

Phase III of this case study is also designated as a highly integrated alternative development initiative to show the linkages of all essential inputs with outputs and their positive spillovers. I will show in future that the input set (RE-SKILL) and output set (HELP) in the alternative development framework can be inexpensively procured, produced, and localized in rural areas like JABA. The development from primitive production to modern production systems can be facilitated by off-grid renewables in short but quick steps. This initiative probably will provide opportunities for more positive feedback between and within each inputs and outputs as shown in Figure 6-3. The virtuous positive feedback loops as shown in Figure 6-3 solves many of the intertwined rural problems. This figure also explains the need for a simultaneous integration of the four outputs, HELP, and also the factor inputs, RE-SKILL, for rural production optimization. This co-optimized process is the integration of modern skill and capital goods, which are the outcomes of urban innovations and underemployed land and labor available as rural endowments. The infrastructure necessary for the complete sustainable development will be roads, electric transport, and broadband network. I expect this integrated ADI-RE-HELP-SKILL process to deliver the essential human needs at lesser private and social costs than the conventional dominant fossil-grid compatible process.

This new phase is expected to remotely deliver health, education, and production skills through broadband network inexpensively, often involving volunteers from across the world (as in Wikipedia) for the necessary skill development in the rural area itself. This will make rural production independent of the long-term urban subsidies. In this way rural development can be made competitive, pro-poor and sustainable without participating in the present urban crises of pollution, migration, and climate change. This might also minimize the role of government or large development agencies, as individuals and small organization can participate in the development process in JABA.

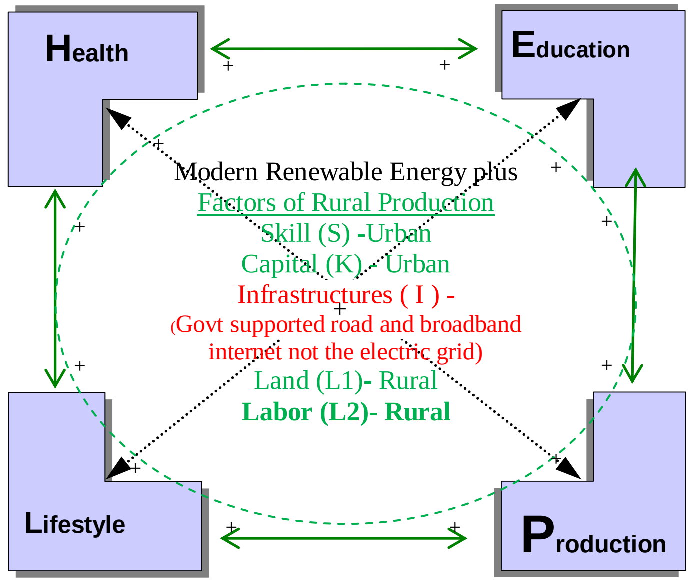

Figure 6-3 Phase III: ADI-RE-SKILL-HELP phase optimized for clean, sustainable rural development (most external factor and output services will use distance based tele-services)

As discussed before, electricity is a derived demand from HELP services, which together drive demand for other input factors, such as more skill, capital, land, and labor. Increased factor incomes will in turn create demand for HELP services in developing rural areas. The important difference between the RE-SKILL and the conventional development process is that the former retains the current traditional societies in their own habitats. It brings in essential skill, capital, and infrastructure using modern wireless ICET and energy efficient transportation network such as off-grid solar energy, cellular phone, internet, tele-services and electric vehicles. The model, however, retains the current healthy lifestyle of using bicycles, walking short distances, and using muscle power for productive activities.

The conventional development paradigm is very intrusive and expensive. It involves large scale physical movement of labor to cities, it breaks down families, it requires the acquisition of land and resources for urbanization, and it needs an expensive transport network. In the conventional development paradigm, as in the cities, the labor force and resources migrate to where only fossil energy, not renewable energy can be extracted or used optimally. Urban skill and capital take decades to accumulate, and they are not able to flow to rural areas as engineers, doctors, architects, and capitalists prefer to live in cities. RE-SKILL turns this paradigm upside down with surprisingly interesting results. There is small scale efficient optimization instead of large scale economies of the dominant fossil-grid systems. However, urban areas will eventually also need to unlearn the skills needed for the fossil grid systems (which I call DE-SKILL) and

RE-SKILL to the new paradigm. My earlier recommendation of removing fossil fuel subsidies and taxing fossil fuels enough to reflect their true costs is appropriate in the urban setting as well. Correct pricing should hasten the day when renewable energy resources are used more in both rural and an urban setting.

I will now show how the development literature should be informed by my experiences of this paradigm shift with the positive spillover effects of small scale environmentally sound systems empower the rural poor, women, and socially backward rural communities.

6.3.2 Small scale economic optimization in Phase III

The rural transformation and skill building from primitive renewable energy to modern renewable energy requires more thorough research and development with deployment of these small scale production systems in one village at a time. Many of the renewable based capital and skills are emerging rapidly and are even gradually being adopted by industrial nations to satisfy their increasing distaste for fossil-grid energy. The rural interest of sustainable development can also be well integrated with such emerging urban RE technologies such LED lighting and display, SPVs, smart phones, e-readers, rechargeable batteries, electric vehicles, and green manufacturing. Although I cannot go into a quantitative general equilibrium development analysis, which I leave for a future study by interested researchers, I will conclude this chapter with how this phase is being implemented in the JABA village and with some of the positive results.

This phase helped us to use rural labor and land more productively. More than twenty jobs have been created, reverse migration has been apparent with about five semi-skilled workers returning to the village, land prices have increased with the school and other civic facilities installed in the village. Instead of massive labor following the fossil-grid urban production system, the smaller RE-SKILL production system has followed the energy resources, labor, land and consumers, all available in the villages. The higher factor incomes will eventually lead to rural empowerment, gradually increasing the bargaining strength of the rural poor and empowering them with access to better services. The inefficient transportation of energy, resources, labor, and final products has been minimized. The productive use of off-grid renewables will now support a transition from primitive skill to a modern RE-SKILL without destroying the core village social fabric of living for food, festivals, friends, and freedom.

Some villagers have developed a “can-do” attitude by experimenting with smaller but modern devices and modular production systems instead of depending on donors for all these services as subsidies that reduce the incentive to work and develop skills. Fortunately, modern technologies to achieve all the multiple but complementary inputs and outputs are available in small, modular, and flexible form with some help from modern technology suppliers or social entrepreneurs. They can experiment on their own and learn to optimize their welfare at much lower costs than is possible in the fossil-grid development system. This case study experience brings an interesting insight to the unintended consequences of the foreign aid that often goes to subsidize urban infrastructure, civic supply and slum rehabilitation as a magnate of more in-migration and more fossil fuel consumption with attendant externality costs. These involve very expensive transitions: fossil-grid powered homes, business plants and transport infrastructure will need renewal to make them suitable for the new renewable energy paradigm; capital and skill already deployed in the fossil-grid may get stranded; and customer education to make behavioral changes is also costly. International development agencies still subsidize the urban development projects which do not need any subsidies. They, however, do not provide adequate services to rural areas which can achieve clean development with a fraction of the urban subsidies diverted as investments for social and physical infrastructure for rural development. The long and oblique path to fossil infrastructure development and back to renewables can be avoided through the ADI-RE-SKILL-HELP model and should be further studied. A pleasant surprise of this new model is that while achieving small scale village level development, it can also gradually be extended to other villages. This will ultimately lead to large scale manufacturing and distribution economies for renewables and efficiency across all the nations of the world, poor or rich.

6.3.3 Summary and potential funding: Emission /carbon offset trading

The main implication of my study is that fossil-grid systems, with their high distribution costs, poor reliability, and market inefficiency play no role for sustainable development of poor rural economies. I have argued that once households, communities, and the rural economies are self-sufficient in rural energy along with the missing factor inputs (skill, capital, infrastructure) to meet their HELP needs, the demand for cross-subsidies from the urban rich will be moot. I also showed that the villagers might not migrate to cities if they can adopt off grid SPV and other renewables and receive urban like amenities in rural areas. The “rurban” villages will undergo such a transition to prosperity without losing sustainability using modern technologies. These modern villages also harness the benefits of globalization of health, education, entertainment and other lifestyle support services through wide spread ICET use without losing control over local production. This is in sharp contrast to the top-down input-output production models used by the central planners with disastrous results in the fossil-grid system.

International support and obligation for climate support might grow as unbundled rural and urban energy markets are made clean and efficient. The climate change debate must focus on how much money can be saved in no regrets-rural solar electrification and on how much global warming gas can be reduced through reduced migration to cities.

The village economy can greatly benefit from the expansion of renewable energy industries. This would be true both for harnessing renewable resources at the local level and for creating a renewable energy industrial base that would serve local markets. This self-sustaining model, which is expected to be subsidy-free, will be run by market entrepreneurs who can borrow investment funds from international and national funds created from the emission taxes or from trading emission credits. In this process, we could see that the sustainable development model meets the perfectly competitive market in rural poor economies of the world. The remaining barriers to the market, such as the lack of roads, health, education, and internet connectivity, can be initially supplied by the government and development agencies. Soon, after a threshold level is reached, the skilled workers and entrepreneurs will emerge in the rural areas to take care of the market enabling infrastructure.

The rural poor who do not emit and may never emit pollution by using off-grid renewables can be paid the 3-10 MT CO_2 offset that they would have emitted in urban areas in India or the USA. This will provide significant income growth at the minimum CO_2 price of $30/MT projected in the USA (Nordhaus 2007; British Colombia carbon tax: http://www.carbontax.org). The feasibility of directly providing cash grant to villagers in lieu of migration and emissions to allow them to develop productive skills and invest in renewable energy technology and efficiency will be an interesting study of great global importance. This possibility should be further researched and widely disseminated amongst the donors, investors, and development agencies to bring sustainable development to rural poor economies of the world at the least cost. Such a policy will, simultaneously, bring many positive benefits including more competitive markets, clean energy, and rural development.

CHAPTER-7

CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

Almost half of India's 80 million rural households lack electricity even after 125 years of electrification. Even urban customers use battery backup systems because of the unreliable grid electricity. The longer and more frequent power interruptions in the villages lead to the use of ancient energy forms in rural areas. Poor or rich, electrified or not, many still use kerosene lanterns. This motivated me to study why all the rural poor economies in the world have not solved these problems when off-grid SPV technology is emerging as an important source of small scale electricity. SPVs can power most of the modern electrical devices and gadgets, which are getting more efficient day by day. I show that such modern gadgets can be used by poor homes in developing countries to leapfrog to the new century of modern renewable energy and energy efficiency.

My literature review identified three drivers of poor rural grid conditions: rurality, poverty, and power market inefficiency that lead to the perpetual subsidies and a vicious cycle of underinvestment and high costs.

Rurality drives the high peak demand for electricity. Availability of biomass encourages heating energy bypass. Poverty is widespread. With average rural household income of about $100/month, many families use low or no grid electricity. This poverty also leads to the lack of demand for refrigeration, low community and street lighting loads, and low rural business and industry loads, which also contribute to low utilization. Thus, the electricity market fails for several reasons. Very low demand and high average costs of a natural monopolistic grid fail to provide enough revenues. Political support and subsidies attract politically savvy bureaucrats or entrepreneurs that depend on the subsidies and government contracts to perpetuate the monopoly. Electricity market inefficiency results from the regulated monopoly dependent on subsidies and plagued by lack of choice, moral hazard, adverse selection, and elite capture. Political entrepreneurs try maximizing profit from government subsidies, innovative accounting practices, spending resources on government patronage, or the political process of regulation rather than focusing on innovation, value creation, and cost reduction. The “market entrepreneurs” who seek profit by creating customer value and reducing supply costs cannot enter in this environment even if the market is no longer a natural monopolistic with emerging SPVs.

I showed that the existing non-transparencies and anti-competitive nature of the current rural grid when jointly managed with the urban grid has led to the investment, operating, and usage inefficiencies in the long rural grid supply chain. The rural grid franchise monopolies are considered unavoidable now or in the future with the hope that funding can be supplied through cross subsidies from the profitable urban and industrial consumers. However, the data and evidence in the Indian power sector from the last two decades do not support the sustainability of cross subsidies, nor do they imply that grid supply to the remaining 80 million off-grid homes will lead to higher revenue and better quality of power. On the contrary, they show ballooning losses and administrative mispricing of electricity leading to the choking off of funds to the otherwise profitable urban power sectors. They further suggest that government investments in an outdated rural subsidized grid are inhibiting emerging competitive and innovative off-grid SPV technologies.

This study is timely, appropriate, and provides counter intuitive results about the rural fossil-grid framework, as the developmental economist and central planners might argue in favor of continued fossil-grid subsidies. It is often argued that subsidies are, in any case, not large, in absolute dollar terms, because the needs of the poor are small, and perhaps international donors would not mind providing these subsidies. Both these arguments were found unconvincing and counterproductive based on this research. The supposedly small subsidies have created larger problems of fossil-grid inefficiencies in the entire supply chain from production and operation to the end use devices. International aid has never been adequate or poor-friendly. Government subsidies of the fossil-grid system not only perpetuate inefficiencies, but they compound the problem of lock-in and retard a transition to clean development. It is perhaps better to make the system clean, competitive, climate friendly and compatible with rural culture so that subsidies will not be required.

In spite of the many market failures of the fossil-grid paradigm, the literature shows that the electric grid networks function relatively well for urban and rural areas of developed high-income countries. With the grid having no substitute in the advanced countries, the literature also shows that developed countries like the USA can probably replace fossil fuels with renewable energy systems to be delivered through the same grid, though at a somewhat higher cost, but these costs are affordable due to their high incomes. In the last century, when the off grid-technologies such as SPVs were not mature enough as a credible substitute, the rural grid was the only option left, and USA style rural electrification was ported to mid-income and rural poor economies of the world.

The release of this research study is especially timely due to two recent but important missions of the Indian government that were unknown to me when I first started this research. First is the Rajiv Gandhi Grameen Vidyutikaran Yojana (RGGVY), a rural grid expansion mission that started in 2005 to provide rural grid electricity to the remaining 80 million un-electrified homes. Second is the Jawaharlal Nehru National Solar Mission (JNNMS), an SPV expansion mission, proposed very recently in 2010, within the grid framework to remove fossil externalities costs from the grid. My study finds both of these solutions inferior to the off-grid SPV as reviewed below.

Solar electricity triggered my attention during my early engineering education, but at that time the technology was in its initial state, though it's potential to remove hunger from the world through water pumping was being discussed 25 years back. Within solar electricity, I explored two options, the SPV-off-grid and SPV-grid options with results as noted below

Four research questions were formulated to see if the highly subsidized RGGVY option is the best electrification option for the rural poor as opposed to off-grid SPVs. Although such SPVs are one of the costliest renewable energy technologies, they are highly valuable due to their portability, modular properties, and complementary to the platter of cheap rural biomass and biogas technologies that can provide heat.

A village case study was designed around the author's native JABA village to experiment with off-grid solar electrification and gather data on technological feasibility, cost, demand, and other implementation issues. This study provided the primary survey data for the cost and demand analysis and showed the opportunities and the barriers to entry of modern technologies that need more policy action. The grid cost data were collected from the Indian government's recent national rural electrification program and solar cost data was taken from the local market in Orissa. My village-level case study provided the income, energy expenditures, and demographic data from 98 households for a unique semi log demand curve for lighting that included both kerosene and electricity costs.

The integrated demand and supply analysis of the grid and SPVs showed that grid is cheaper only if the rural grid can be supplied at ½ kW peak load and inefficient appliances are used by the poor villagers for consumption of 30kWh/month of electricity as dictated by the Indian government. I found off-grid SPV electricity is cheaper than grid electricity for the rural poor in India when they use efficient appliances and devices. Under the more efficient use of 10 kWh/month, the advanced CFL/LED devices can be used for the same or better quality of service.

The grid average cost then becomes higher than solar electricity by a factor of two due to efficiency. I found the grid average cost is so high because of the higher peak time use with high variable costs, high fixed costs of longer distribution lines, larger distribution losses, and higher operation and maintenance costs in rural areas that cannot be distributed to the non-existent rich customers or industries in rural areas. This expensive marginal energy costs more than 12c/kWh in the wholesale market with additional costs of the losses of 35% and more when transported through long transmission and distribution lines. Additional distribution investment is conservatively estimated at $460/kW. High operation and maintenance costs add another 5-7% depending on the terrain and remoteness of the villages. The average cost for a 30 kWh per month of electricity supply could be in the range of 31-45 c/kWh while the revenue earned is only 3-4 c/kWh. The off-grid SPV costs are about 38 c/kWh. The grid is cheaper for the very poor only if consumption is higher than 20kWh/month with maximum capacity demand lower than ½ kW. Such a low capacity is unlikely and also difficult to enforce in a grid environment with metering and technology limitations. SPVs are cheaper when consumption is lower than 20 kWh per month and there is no problem of enforcement and metering as they are off-grid devices and use efficient appliances by design.

On the demand side, I observed that rural demand is very low because of low incomes, off-grid subsidies for kerosene and diesel, and the availability of primitive biomass for cooking and heating. My demand estimates suggest that under no circumstances can the rural grid supply be subsidy-free with the low current villagers' average income below $100/month. The off-grid SPV can be subsidy free for the rural poor in India. Although low economies of scale operate against the grid there are no such diseconomies of scale for modular off-grid SPV systems. Rather, conservation and efficiency are helpful when designing more efficient SPV systems. The rural information, communication, and energy needed to run radios, TVs, cell phones, CFL/LED lamps, and other appliances can all be supplied at the same or lower average cost of around 38c/kWh using SPV based systems instead of grid electricity within the government mandated 30 kWh/month/household.

The break-even household income for the grid to be subsidy free was found to be $200/month for the unrealistically low ½ kW capacity, while the average village household income is less than $100/month. I found that the break-even consumption for a subsidy free grid is 40 kWh for a more realistic connected load of one kW. The threshold household income for this consumption amount is about $400/month. Even with the optimistic assumption of 10% annual income growth, the current rural Indian household income of $100 per month can only increase to $300/month, much less than the threshold income found above. As income grows one could expect that the grid will be cheaper than off-grid SPV. However the learning curve effect makes the off-grid SPV even more attractive. Thus, a subsidy free grid supply cannot be achieved in rural India by 2020 and possibly beyond as the SPV prices are coming down but grid prices are not. The dominant grid firm in the face of open access with no regulatory or market barriers and no preferential taxes and subsidies will eventually lose its dominance and have to compete.

A "dominant firm" model was used to assess the economic feasibility of the grid in rural areas by 2020. The demand model showed that rural demand for grid electricity is very low and the grid average cost is very high. Thus, an unstable monopoly is surviving with unsustainable subsidies. Such low demand in rural areas might be the result of the large use of free and cheaper biomass, biogas, and solar thermal energy relatively easily accessed by low-income rural consumers and will continue in future. In a dynamic framework using learning curves, I showed that even costly renewables like SPV electricity can compete with the rural grid, economically meet the rural demand, reduce the needs for rural energy subsidies, and enable private or community organizations to deliver energy services in competitive markets. The theoretical foundation of the dominant grid firm was used to show that subsidies are not required for SPVs now or in future, while the energy and development experts agree that the rural grid will continue requiring subsidies for a long time to come.

Under JNNMS, the SPV-grid along with other renewable grid options are being suggested for India as a panacea for climate change, recent high increases in grid prices, fossil fuel scarcity, and pollution control. Its target is to expand to 20,000 MW SPV and large solar thermal power generation by 2022. Though JNNMS has an off-grid SPV component, it is small at less than 200 MW by 2013 and only 2000 MW by 2022. These grid connected SPVs do not solve the large investment costs and high losses of the Indian distribution system, which can be avoided if off-grid SPVs are deployed. This study found that pursuing a highly subsidized SPV-grid neglecting the opportunities of subsidy-free off-grid SPV will compound the problems of subsidies and anticompetitive outcomes. The SPV-grid has the potential to be the next economic disaster after the recent power sector privatization debacle of the last decade. Grid connected large scale SPV systems are considerably more expensive than the fossil grid and would carry with them the current inefficiencies, moral hazards and adverse selection, which have already mired the Indian grid with revenue and investment deficiencies. It would not remove the essential rural problems of low access and high costs but would rather delay investment in a sustainable future and likely require continued fossil fuel use through off-grid kerosene lanterns, diesel pumps and gasoline generators negating whatever environmental benefits SPV would have created in the grid. Further, the entire 20,000 MW future solar mission is hinged on the funding available from the

UNFCC, which is doubtful after the failure of Copenhagen talks. I found that the grid based "solar mission" is the most expensive option and would do even more to crowd out a far better solution of off-grid SPV based sustainable rural development.

My biggest surprise from the above work is that the SPV can be subsidy-free for the rural poor in India. My second surprise is that electricity demand is very low and a small amount of reliable quality electricity can meet the needs of rural home and community to make them modern and productive. With such low demand, the grid will never be subsidy-free. SPV delivered through the grid will be much more expensive than the fossil-grid, and the urban sector will be required to cross-subsidize most of these high costs. The supposed clean nature of an SPV-grid will also be lost due to the unreliable nature of the Indian grid needing more fossil-fuel powered decentralized small generators or kerosene.

If the grid is economically inferior up to 2020 and the alternative can be provided subsidy-free even today, it does not make any economic sense to subsidize the grid in the name of the poor and perpetuate a non-working government subsidized grid-monopoly in rural India. An often ignored important economic benefit of off-grid systems in rural India is the creation of a competitive clean energy market. This market could possibly end the electricity monopoly and energy deprivation in the same way that modern cell phone technology erased the telecom monopoly and communication deprivation in rural India. Recently, cell phone industries, through competition and wireless infrastructure, have provided low-cost communication service at $2/month. This has led to heavy customer sign ups to build the volume necessary for a scale economy that the wired telephone business could not provide earlier. Thus, while the wired telecom business is subsidized in rural areas of India, the cellular business is unsubsidized and multiple market players have entered with huge investment funds. Similar options are available for multiple competitive players to supply rural energy services for $2 per month solar lanterns to $10/month ICET services. But this cannot easily be done in the monopolistic grid framework.

I also explored development issues in my three phased development initiatives at JABA village. They showed that the porting of the inefficient fossil-grid has not worked and porting the renewable grid technologies to rural poor economies may also be a disaster for rural poor economies. On the contrary, the case study experiences and the cost and demand analyses suggested a completely separate off-grid market for the rural poor. In this market, demand clears for SPV electricity with no burdens of subsidies, externality costs, and elite capture. The barriers to entry identified in Phase I need government action to remove subsidies and promote off –grid SPVs in rural India immediately. Phase II showed the need to focus on resource mobilization for the unmet social issues of land reform, health, social security, insurance, internet broadband, and physical infrastructure that are often impossible to implement in the private sector. The control of energy services in rural areas can be left to the millions of market entrepreneurs to innovate and search for reliable, affordable, and safe local renewable energy, and not to seek subsidies as in the present fossil-grid regime. The third phase of the case study recommends economic development efforts that can foster local renewable energy generation, equipment manufacturing, energy services, and diversified production capacity in rural areas itself leading to the final ADI-RE-SKILL-HELP phase of development. In this alternative development initiative (ADI), the village produces the final outputs of health, education, lifestyle, and other products/services (HELP) in a phased manner starting from a very small scale with minimal subsidies and using renewable energy and resource efficient technologies (RE) not possible in a large scale fossil-grid system. This step will require a happy combination of rapidly growing modern urban skill and capital in RE sectors to be used to modernize villages with their vast endowment of unemployed land and labor. These four factor resources can be combined together only when the physical infrastructure such as roads and broadband services (referred to here as SK-I-LL) are made available for remote operation of ADI-RE–HELP projects. This will increase the availability of skilled labor, credit, social security, and insurances in the village through partnerships with the local technical and skill training institutions, micro finance organizations, infrastructure providers, and many philanthropic individuals or small organizations. Government and large funding institutions can help accelerate this process but are not essential for this model to work. The donors and investors can directly watch online as their investments remove poverty and hardship through the internet and ICET.

On the developmental aspects of the off-grid SPV, my biggest surprise came from the case study experience as the solar lights could not on their own bring any appreciable development other than the lifestyle improvement and villagers showed very little willingness to pay the fees. But when the complementary input factors were provided, the productive capacity of the villagers and social outputs such as health and education could be improved. These positive externalities require larger investments in the non-energy sectors and the lumpy grid investment at huge costs cannot achieve these multiple investment needs. The off-grid SPVs, however, could meet the phased development plan much easier at lower costs without any stranded capacity due to their modularity. My last surprise was how the off-grid SPVs funded through a reasonable emission tax will be less expensive for India than the costs of the current fossil-grid system. While the more developed world's urban utilities still struggle to incorporate renewable energy and energy efficiency in their business model, India's poor can build these resources from the ground up.

Each of the three case study pahses showed that development does not involve a large amount of energy but requires reliable, portable, and affordable local renewable resources backed by modern efficient devices. Many social and under development problems, no doubt, stand as barriers to entry. But these problems can be addressed through learning by doing, providing accurate price signals, better education on the costs and benefits of the SPV technologies, and the removal of other market failures.

In essence, I suggested a more optimized rural economic development model that can be taken up by numerous searchers in tiny steps but that will be a giant step by the larger society for a sustainable world. The core infrastructure to achieve these will be the efficient rural roads and broadband internet connectivity to create a bidirectional flow of resources between rural and urban areas. The core financing mechanism can be the savings from the existing inefficiencies of the fossil-grid, future savings from the off-grid SPV, and the transfer of emission credits and emission taxes.

The rural electrification study through off-grid systems has not been getting enough attention in the academic literature for lack of funding. The costs and benefits of other renewables in various rural settings must be examined in more detail and should cover larger areas than the one village done in this study. From the time of the data collection and analysis, many new conservation and efficiency measures have been introduced in modern appliances, and the rural grid loads have declined further, which our demand analysis has not captured. It might be useful to observe the new demand curves of the villages, which we postulate will be much lower than what the 2003 data indicates.

It is possible for the academic, large donors and multilateral development agencies to take up more such interdisciplinary studies that might change their current focus on the grid based solutions. More research can be done on funding for clean development and income transfer to the rural poor. Along these lines, I plan to do further empirical research to learn more about the consumption behaviors of poor households and especially women to any payments for emission credits if introduced later. Transfers of emission credits to households or to the bank account of the homemaker women may be a good mechanism as demonstrated by Md Yunus of Garmin Bank, through his novel micro finance, and Bunker Roy, through his Barefoot college training to women in solar technologies. Studying the choices and allocations of households and women for HELP services will determine if paternalistic government targeting of a specific sector provides more social welfare than a more liberal direct cash payment.

The partial equilibrium cost and demand theory presented in this thesis for an ideal subsidy-free rural electricity market may not work in practice due to large scale underdevelopment and missing complementary inputs and outputs. A new case study of a co-optimized rural production in a general equilibrium framework may be taken up for further study if not yet done by interested development economists and policy planners. The optimization of inputs and outputs in this initiative does not require sophisticated linear programming, but rather techno economic study of the cost and demand of the small scale health, education, and production projects of the villagers. As the villagers see and use the new technologies finding them affordable and operable in their own home and communities, off-grid renewable systems will not only improve their quality of life but will also develop a thriving, market-based optimization of input and outputs. Thus, future study should focus on how to bring such modern technologies and a competitive market to the rural world, where the inherent sustainability and prosperity do not require fossil fuel or a migration to cities run by fossil fuel. This proposal, I believe, will reduce the growth and level of current global warming faster than the present regime of unending negotiations on who should start cutting greenhouse gases first. The climate change debate should include and monetize the huge potential of the rural world as a source of sustainability. More work should be done to investigate how the fossil fuel emission charges can be passed on to the rural poor as social security or for market penetration of clean energy in an off-grid framework for poor economies to thrive and sustain both their conservation culture and the planet.

This research, though long, complicated, and continuing gives me satisfaction because of its potential and timely implications for the world's rural poor world. That a subsidy free electricity service is possible in rural India and has great implications not only for the rural poor in India but for the entire population of other countries that are rural, poor, and have electricity market inefficiencies. It not only indicates the efficient technological solutions for the core poverty and rural deprivation issues that have bothered me for over a decade, but it also suggests future solutions to global warming and sustainability issues that were not in my original research agenda. It is up to humanity to take the next steps to end the global warming debate by solving rural problems that will not only reduce rural poverty and pollution through modern health, education, lifestyle, and productive services but also regulate the fossil fuel based urban development and pollution and reduce or reversed migration to urban areas.

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