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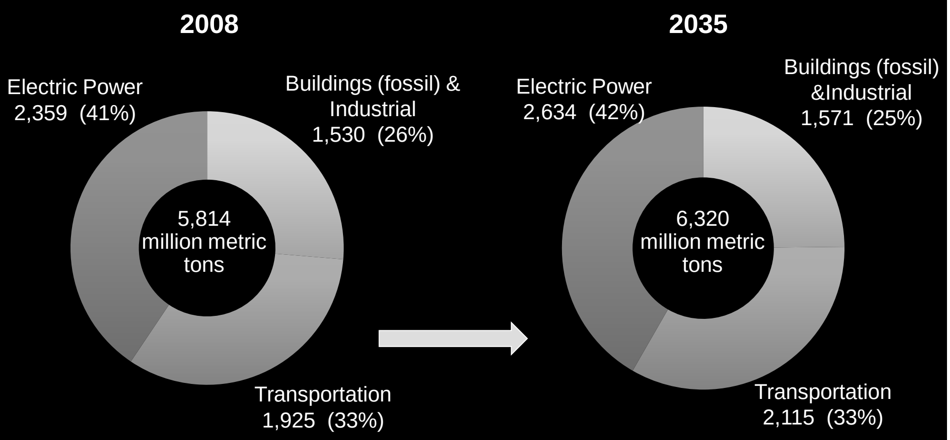
Varun Mehra, Dr. Claudio Vergara	**Data Analysis**
Dan Strawser	**Embedded Control**
Prof. David Hsu	**Field Experiments**

Electric Power Contribution to CO_2 Emission

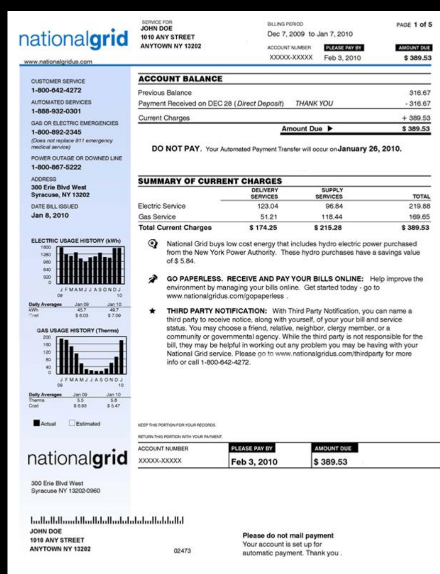


Source: *Annual Energy Outlook 2010*

Historically, electrical power has been the largest source of CO_2 emissions, the main contributor to climate change. But in the upcoming decades electricity can become a key lever in evolving towards a low carbon economy.

- International Electricity Partnership, Dec. 2009

User Interaction with the Electricity Grid



nationalgrid

www.nationalgridus.com

SERVICE FOR
JOHN DOE
1010 ANY STREET
ANYTOWN NY 13202

BILLING PERIOD
Dec 7, 2009 to Jan 7, 2010

PAGE **1 of 5**

ACCOUNT NUMBER	PLEASE PAY BY	AMOUNT DUE
XXXXX-XXXXX	Feb 3, 2010	**$ 389.53**

CUSTOMER SERVICE
1-800-642-4272
AUTOMATED SERVICES
1-888-932-0301
GAS OR ELECTRIC EMERGENCIES
1-800-892-2345
(Does not replace 911 emergency medical service)
POWER OUTAGE OR DOWNED LINE
1-800-867-5222
ADDRESS
300 Erie Blvd West
Syracuse, NY 13202
DATE BILL ISSUED
Jan 8, 2010

ACCOUNT BALANCE

Previous Balance		316.67
Payment Received on DEC 28 (*Direct Deposit*)	*THANK YOU*	- 316.67
Current Charges		+ 389.53
	Amount Due ▶	**$ 389.53**

DO NOT PAY. Your Automated Payment Transfer will occur on **January 26, 2010.**

SUMMARY OF CURRENT CHARGES

	DELIVERY SERVICES	SUPPLY SERVICES	TOTAL
Electric Service	123.04	96.84	219.88
Gas Service	51.21	118.44	169.65
Total Current Charges	**$ 174.25**	**$ 215.28**	**$ 389.53**

National Grid buys low cost energy that includes hydro electric power purchased from the New York Power Authority. These hydro purchases have a savings value of $ 5.84.

GO PAPERLESS. RECEIVE AND PAY YOUR BILLS ONLINE: Help improve the environment by managing your bills online. Get started today - go to www.nationalgridus.com/gopaperless .

★ **THIRD PARTY NOTIFICATION:** With Third Party Notification, you can name a third party to receive notice, along with yourself, of your your bill and service status. You may choose a friend, relative, neighbor, clergy member, or a community or governmental agency. While the third party is not responsible for the bill, they may be helpful in working out any problem you may be having with your National Grid service. Please go to www.nationalgridus.com/thirdparty for more info or call 1-800-642-4272.

ELECTRIC USAGE HISTORY (kWh)

Daily Averages	Jan 09	Jan 10
kWh	45.7	49.7
Cost	$ 6.03	$ 7.09

GAS USAGE HISTORY (Therms)

Daily Averages	Jan 09	Jan 10
Therms	5.5	5.8
Cost	$ 6.93	$ 5.47

■ Actual □ Estimated

KEEP THIS PORTION FOR YOUR RECORDS.

RETURN THIS PORTION WITH YOUR PAYMENT.

nationalgrid

300 Erie Blvd West
Syracuse NY 13202-0960

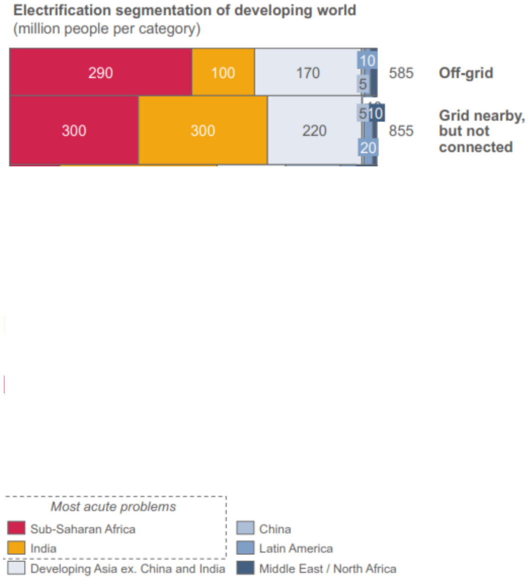
ACCOUNT NUMBER	PLEASE PAY BY	AMOUNT DUE
XXXXX-XXXXX	**Feb 3, 2010**	**$ 389.53**

JOHN DOE
1010 ANY STREET
ANYTOWN NY 13202

02473

Please do not mail payment
Your account is set up for automatic payment. Thank you .

Global Electricity Access

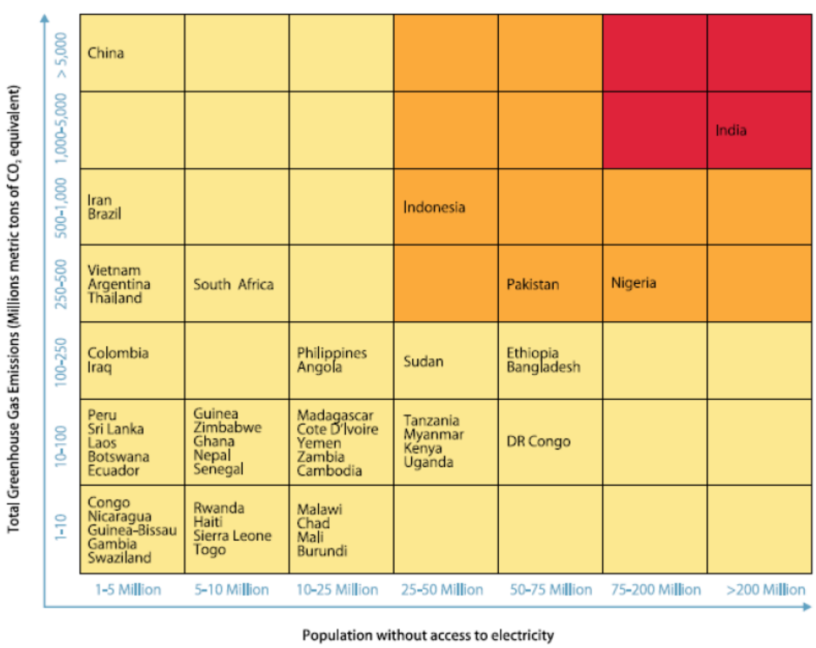


Issues

1. 1.4 B people have no access to electricity

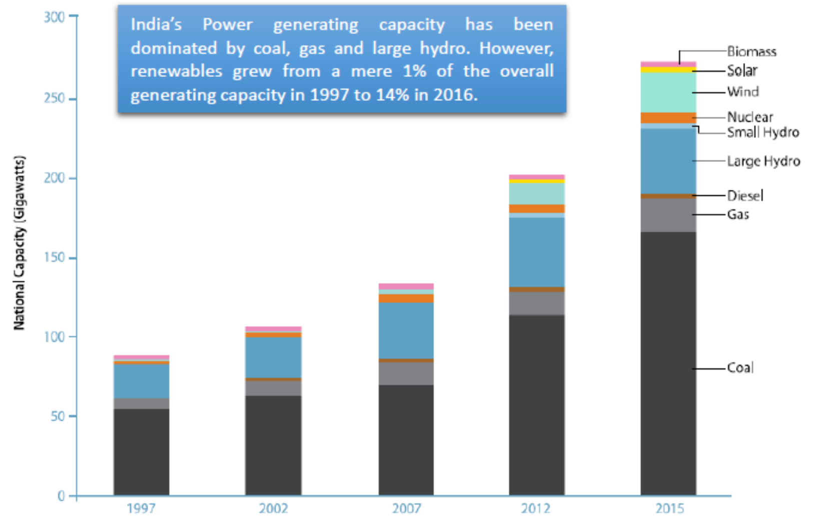
Impact

- Poor health (air pollution, lack of medical services)
- Lower productivity
- Hours of menial labor
- Exclusion from globalizing world



Source: World Bank Development Indicators, 2015;
Intergovernmental Panel on Climate Change, 5th Assessment Report,2014

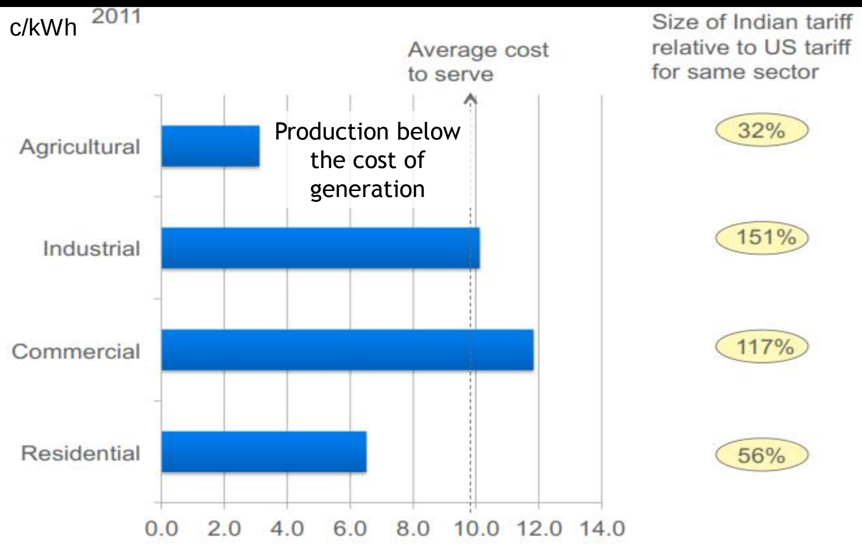
Grid Extension and Increasing Coal



Source: India Central Electricity Authority; March 2015

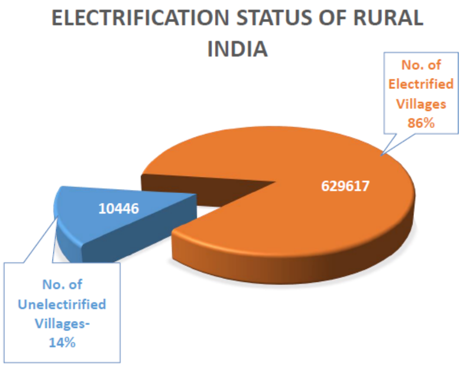
Total Installed Capacity: 304.76 GW (As on 31st July 2016)
Renewable Energy Sources: 44 GW

Electricity Tariffs

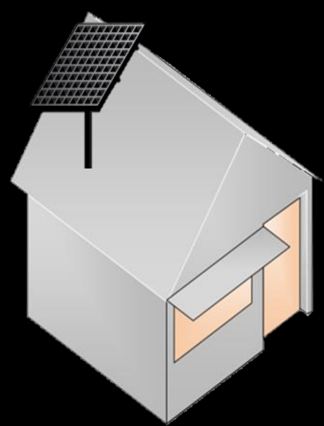


URCE: Government of India Planning Commission, Columbia University, US EIA

The Consequences of Selling Below Cost

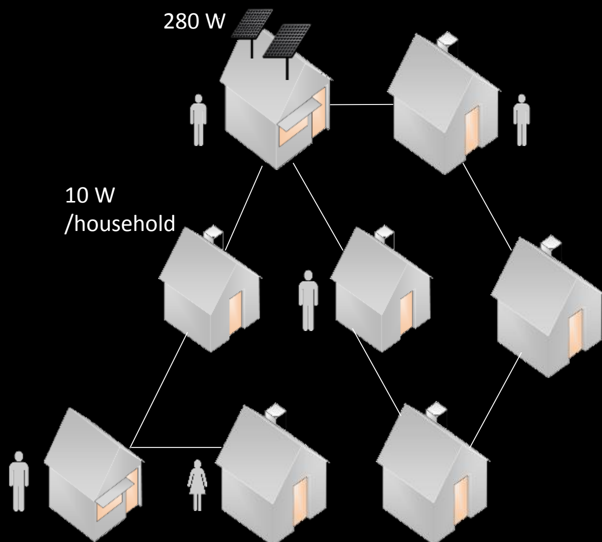


Solar Home Systems



$20/Watt Installed

Solar Microgrids



62,000 Rs ($1000) - capital cost, with PV panel 31% of that cost, batteries 25% and wiring 20%

Challenges of Rural Electrification

Electrification technologies	Factors necessary for wide scale deployment			
	Low initial capital for user	Ease of deployment	Empower users to add generation	Low cost of capacity expansion
 **Electric grid**	✓	✗	✗	✗
 **Individual systems** (e.g. solar, etc.)	✗	✓	✓	✗
 **Traditional microgrids**	✓	✗	✗	✗

Learning by Doing (July 2015)

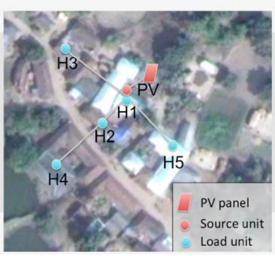
- Work with local CSR (Tata Steel) to survey village needs
- Survey local appliances and PV systems
- Install Solar Home System in 5 households

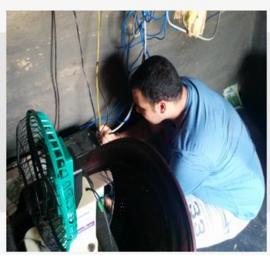
TATA
TATA STEEL

Learning by Doing (August 2016)

- Work with a local entrepreneur to establish a microgrid business in a village
- Recruit (20) customers for the microgrid and establish tariffs
- Install PV system, wiring, and appliances
- Establish maintenance agreement for microgrid

TATA
TATA STEEL





Challenges of Rural Electrification

Electric Grid
- Rural users expect highly subsidized tariff structure
- Grid extension can be expensive for small villages

Individual Systems
- Lack economy of scale for individual installations
- Challenging to extend beyond lighting and charging

Microgrids
- Socialization
- Requires a rigorous planning process
- Involves labor-intensive payment process

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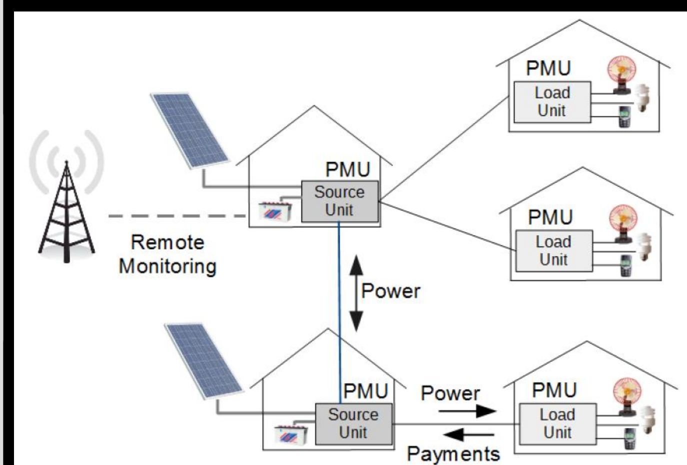
Load Control
- Tiered service
- Load shaping

Collection
- Support for pre-paid metering
- Theft monitoring

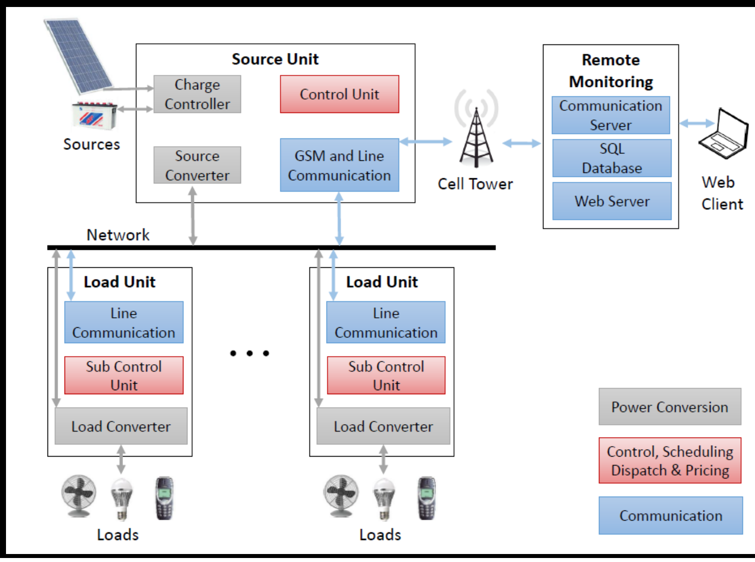
Flexibility
- Dynamic tiers
- Expandable generation



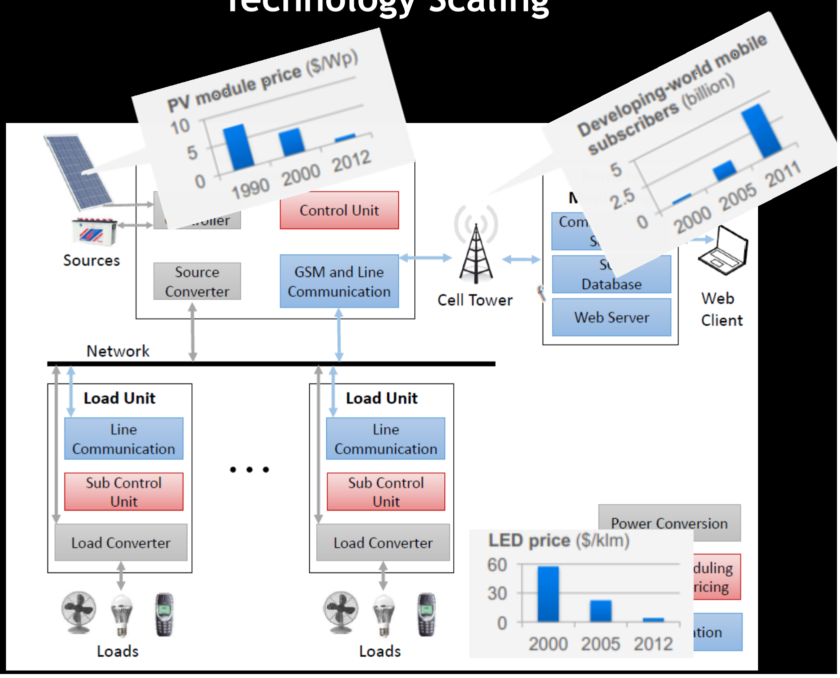
uLink Cost Targets

Prosumer Target Cost: 15,000-20,000 Rs

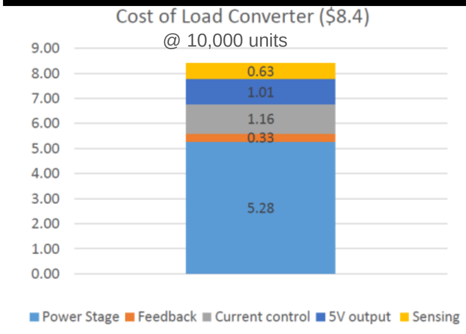
Consumer Target Cost: 1,500-2,000 Rs

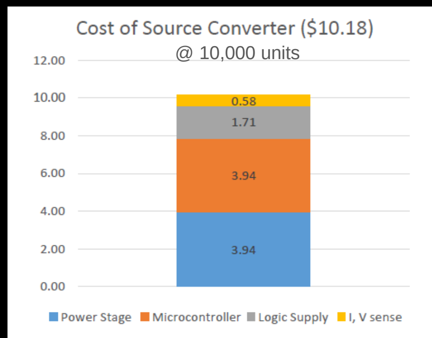


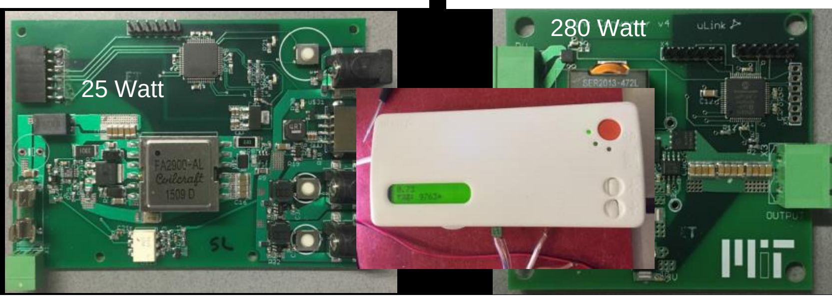
Technology Scaling



uLink Prototype





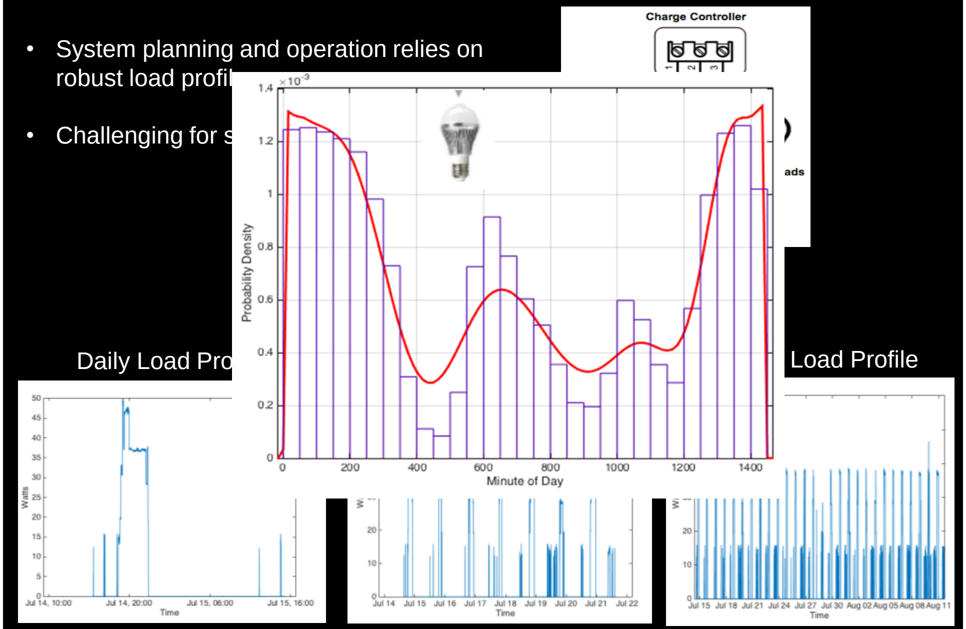


System Sizing with Reliability Constraints

- Acquire inputs (number of consumers, distance, etc.)
- Create demand profiles based on appliances, usage, etc.
- Initialize combinations of available PV and battery sizes
- Input reliability preferences and cost functions of PV, battery
- Iterate to determine reliability levels and generation costs
- Search to determine combinations meeting reliability thresholds
- *Determine final battery and PV combination*
- *Conduct financial analysis (i.e. payback, NPV, DCF, etc.)*

Data Analytics for Load Forecasting

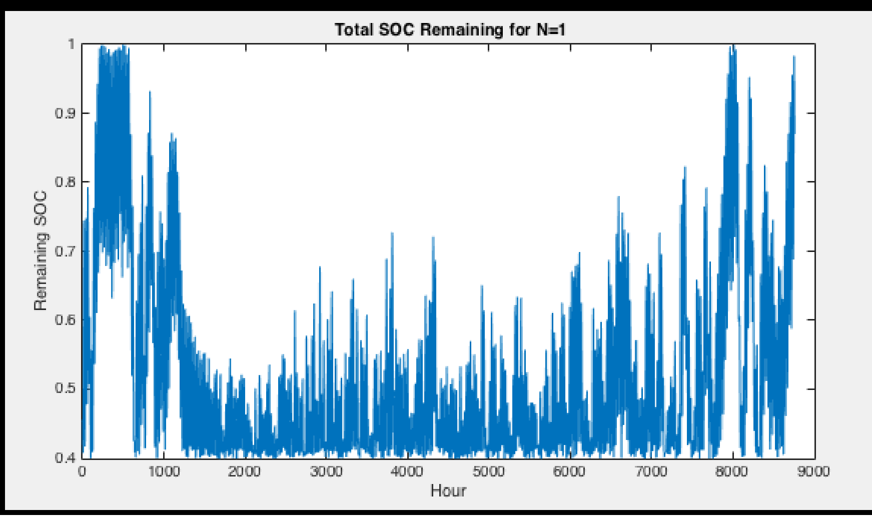
- System planning and operation relies on robust load profil
- Challenging for s



Operational Forecast of PV System

Example SELCO 'Super Bright Home 14 HLS

2x5W CFL's, 4x7W CFL's, 4x11W CFL's, and 2x15W Fans for loads, and a 120W panel and 240Ah lead acid battery



System Sizing with Reliability Constraints

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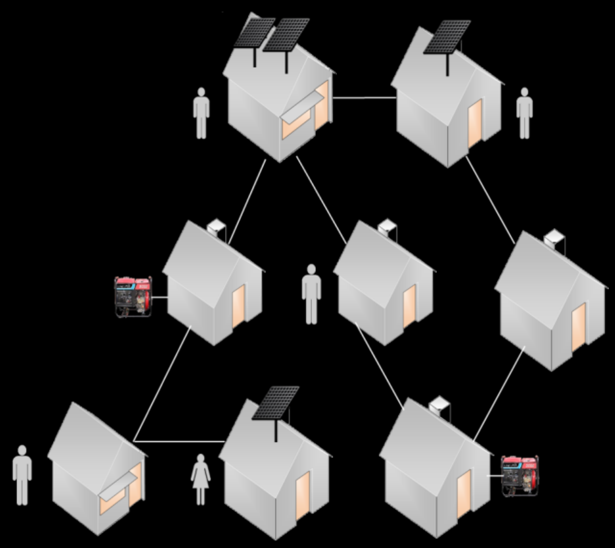
2. Create demand profiles based on appliances, usage, etc.
3. Initialize combinations of available PV and battery sizes
4. Input reliability preferences and cost functions of PV, battery
5. Iterate to determine reliability levels and generation costs
6. Search to determine combinations meeting reliability thresholds
7. *Determine final battery and PV combination*
8. *Conduct financial analysis (i.e. payback, NPV, DCF, etc.)*

System Modeling with Demand Response

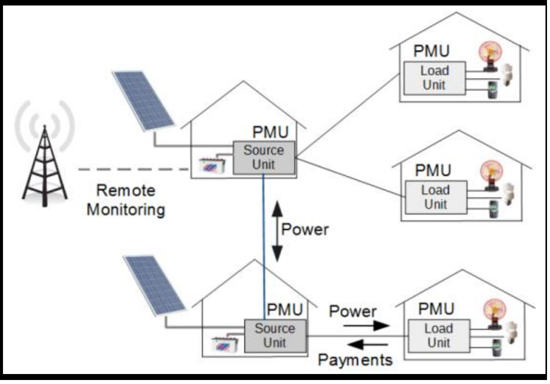
- **Demand inputs**
  - **2 LED's, 1 Fan, 1 Cell phone charger for 5 households**
- **PV module selection: 130 watts**
- **Battery size: 80 ah**
- **LCOE over 5 years: 0.279 ($/kWh)**
- **Capital cost: $3.94**
- **Initial cost (including network): $511**
  - **$15/customer electronics**
  - **$40/prosumer electronics**
- **Breakeven monthly revenue required (with no initial connection fee): $4.76**
- **Breakeven monthly revenue required (with connection fee of $15): $3.96**

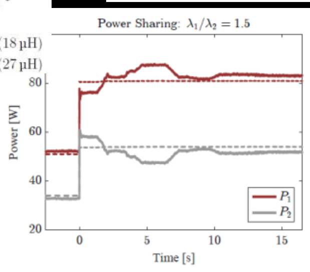
Ad Hoc Expansion of the Microgrid

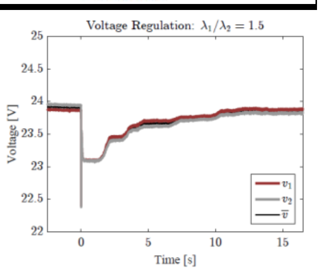


Power Sharing

Predetermined Parameters	
Network Configuration	Distributed Star
Number of Sources	2
Number of Loads	7
Nominal Voltage (V_{ref})	24 V
Total Load Power (p_Σ)	140 W
Max Line Time Constant ($\tau_{\max}$)	0.27 ms
Constraints	
Min Node Voltage ($V_{\min}$)	18 V
Min Distribution Efficiency ($\eta_{\min}$)	90%
Free Parameters	
R Between Source and p_Σ (R_Σ)	$0.22\,\Omega (\leq 0.26\,\Omega)$
Droop Resistance (r_d)	$0.50\,\Omega (\leq 0.51\,\Omega)$
Load Input Capacitance (C)	$80\,\mu\mathrm{F} (\geq 16.7\,\mu\mathrm{F})$
Control Parameters	
Time between messages (T_m)	1.5 s
Voltage gain ($k_{i,v}$)	$0.30\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}$
Power gain ($k_{i,p}$)	$0.017\,\mathrm{W}^{-1}\,\mathrm{s}^{-1}$
Experiment: Line Impedances	
$Z_1 = R_1 + j\omega L_1$	$0.83\,\Omega + j\omega(18\,\mu\mathrm{H})$
$Z_2 = R_2 + j\omega L_2$	$0.10\,\Omega + j\omega(27\,\mu\mathrm{H})$







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