OR in Energy

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Bilkent University

26 Nisan 2017

SUSTAINABLE ENGINEERING LAB.
formerly Modi Research Group

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

İhsan Doğramacı Bilkent Üniversitesi

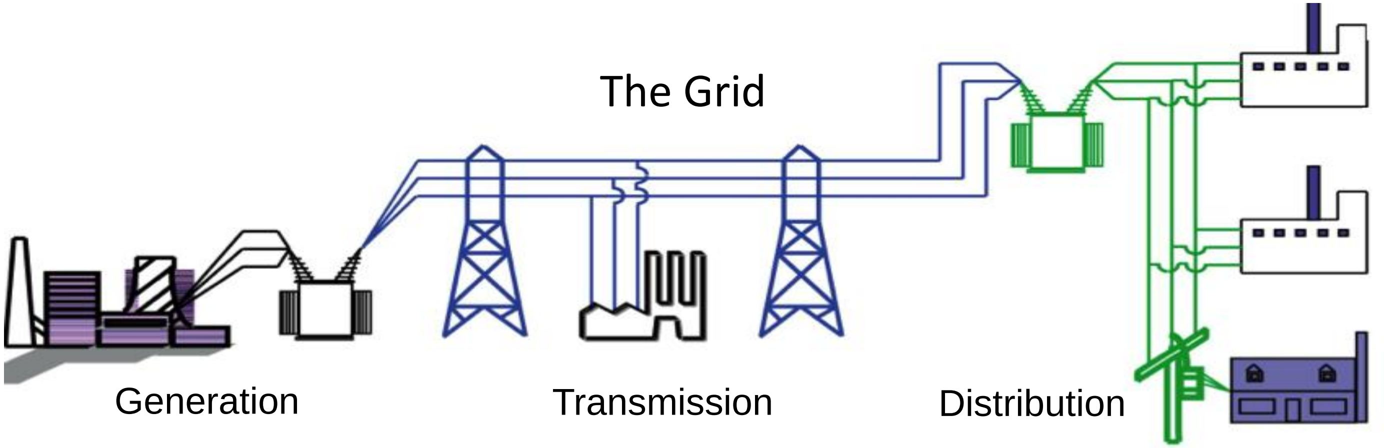
The Goal:

-Design and development of ***economically efficient*** and ***environmentally sustainable*** energy systems

1) for Rural Electrification
   - Power Distribution Systems

2) with Renewable Sources
   - Power Generation and Transmission Systems

-Help policy makers make cost assessments in energy infrastructure planning rapidly and accurately.



Motivation

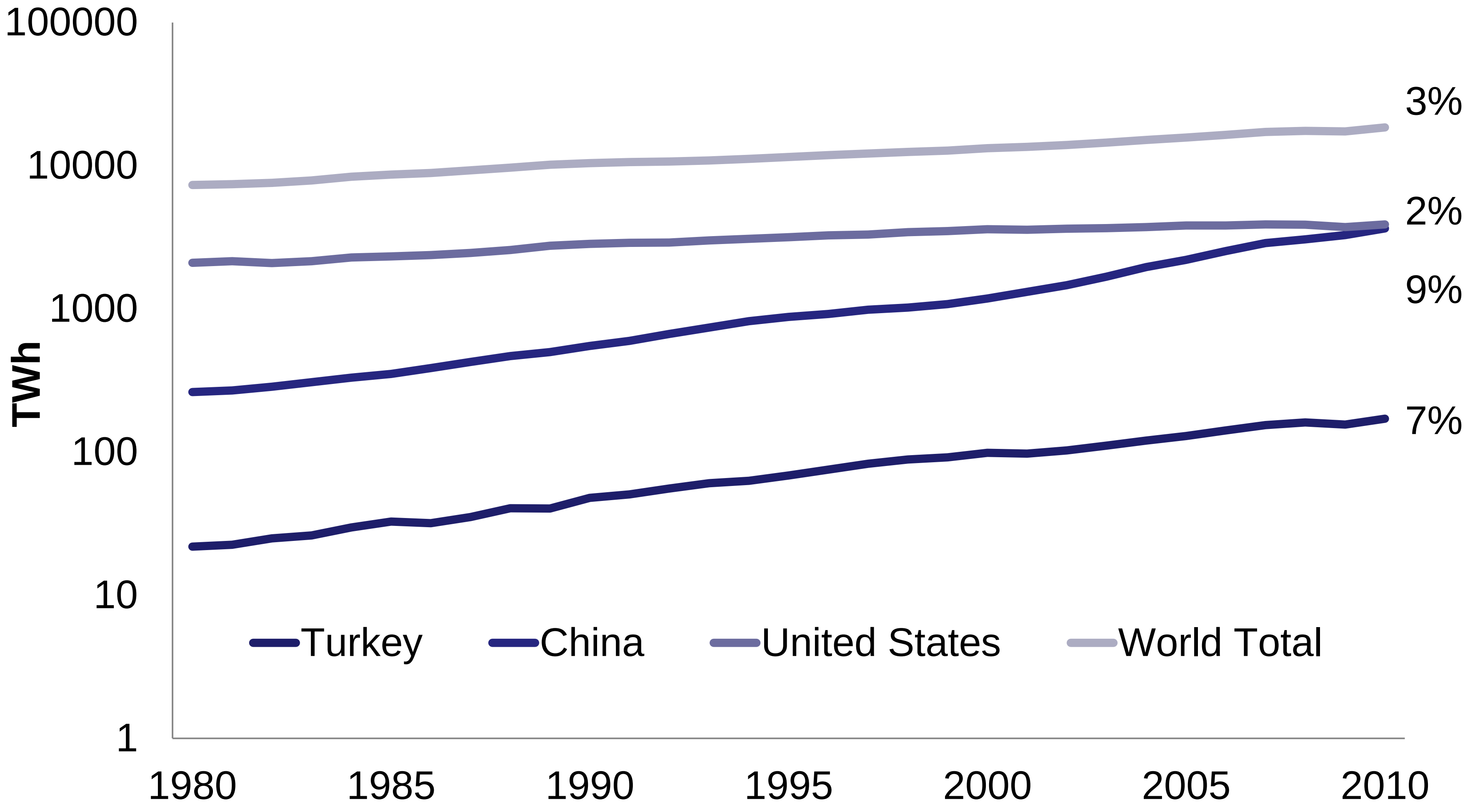
-Rural Electrification

The International Energy Agency estimates that the number of people who do not have access to electricity is nearly 1.1 billion.

This number is expected to increase over the next 30 years unless investments in providing modern energy services are expanded significantly.

Motivation

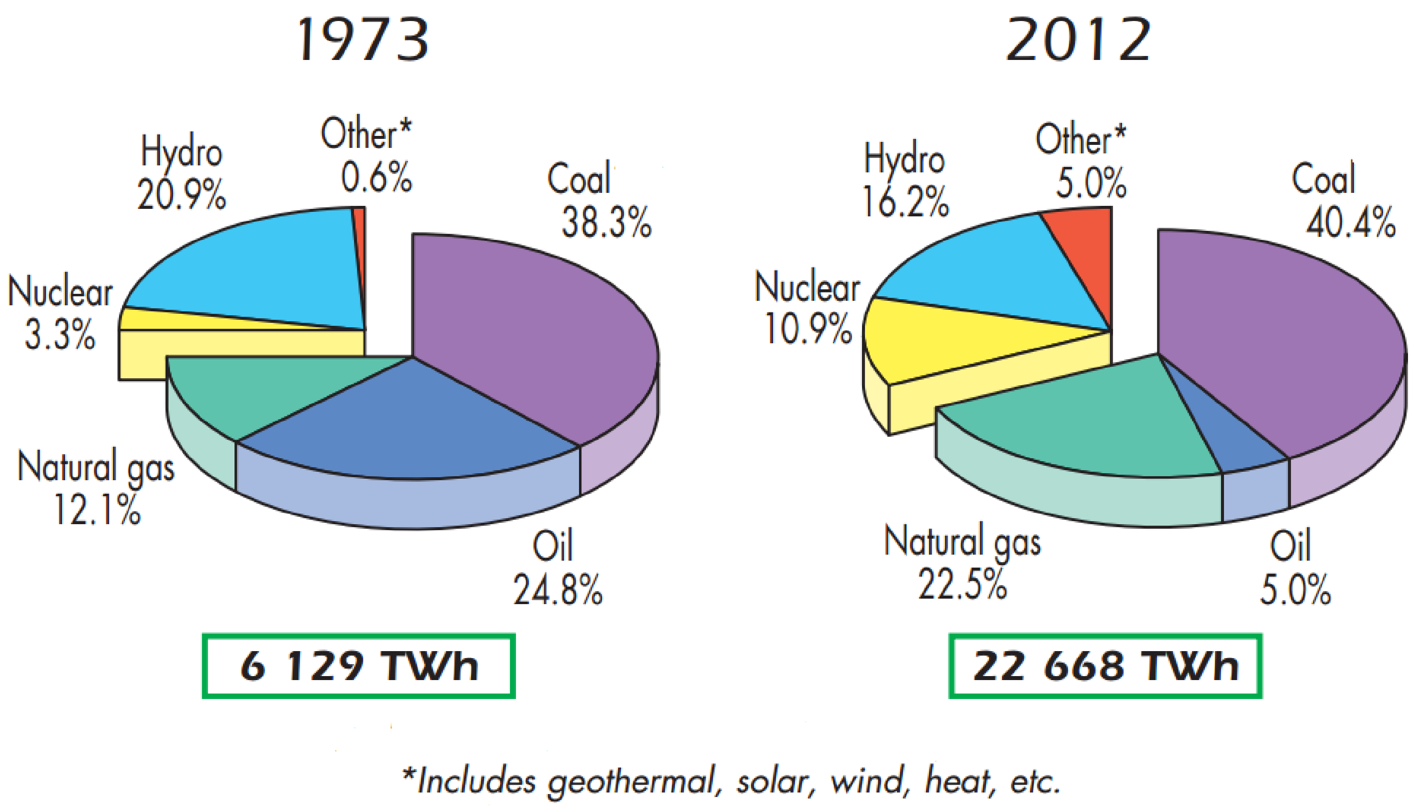
-Demand for electricity increases constantly



Source: Energy Information Administration (EIA)

Motivation

-Current electricity generation mostly relies on fossil fuels.



International Energy Agency, Key World Energy Statistics, 2014

Fossil Fuels

- Finite.

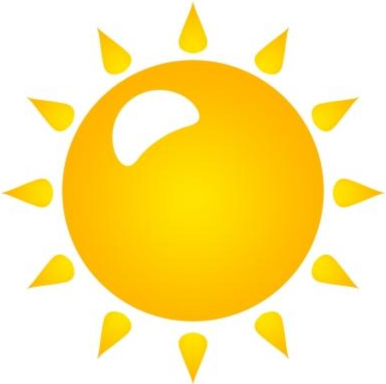
- Shafiee et. al.,2009 estimated the fossil fuel reserve depletion times for oil, coal and gas as approximately 35 ,107 and 37 years, respectively.

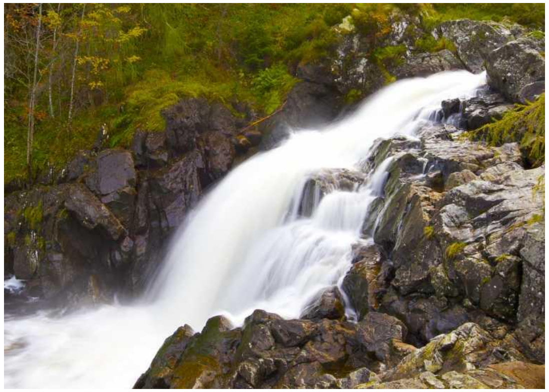
- Coal reserves are available only up to 2112, and will be the only fossil fuel remaining after 2042.

- One of the greatest threats to the environment.
- Necessitates advanced emission control technologies.

- Reliable source of base load power with low operating costs.

Renewable Energy

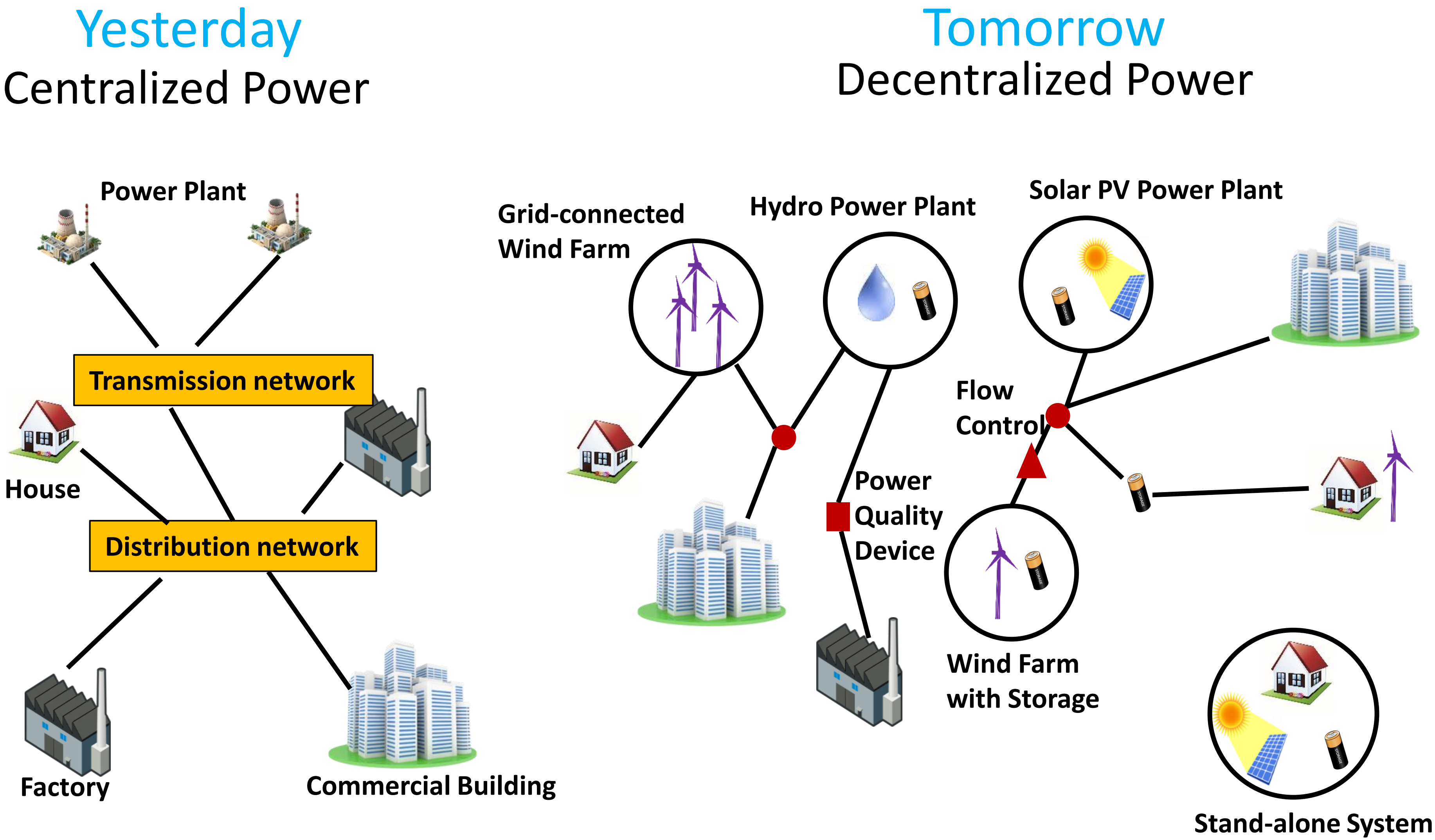


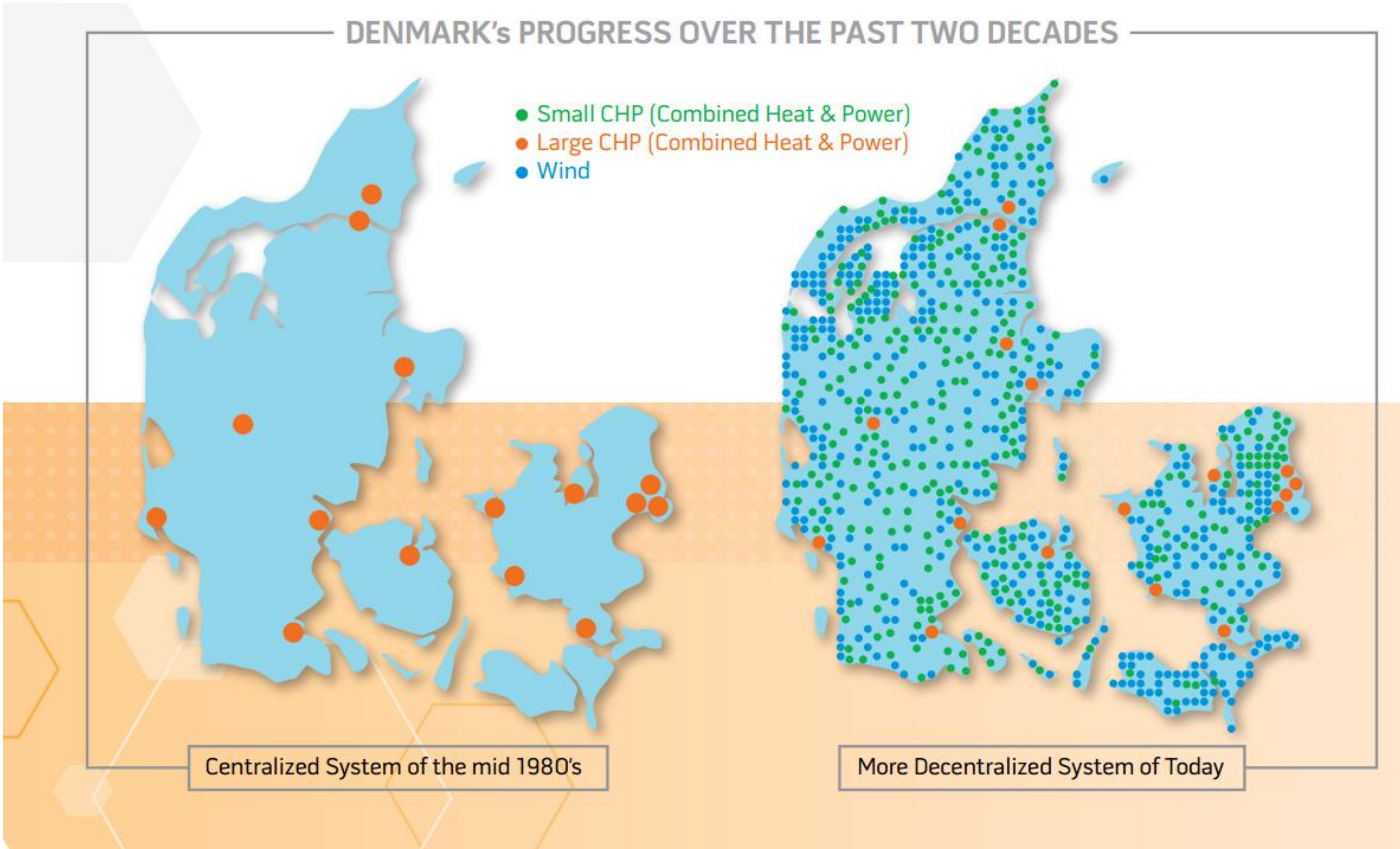


- Biofuel
- Biomass
- Geothermal
- Hydro
- Solar
- Tidal
- Wave

Motivation

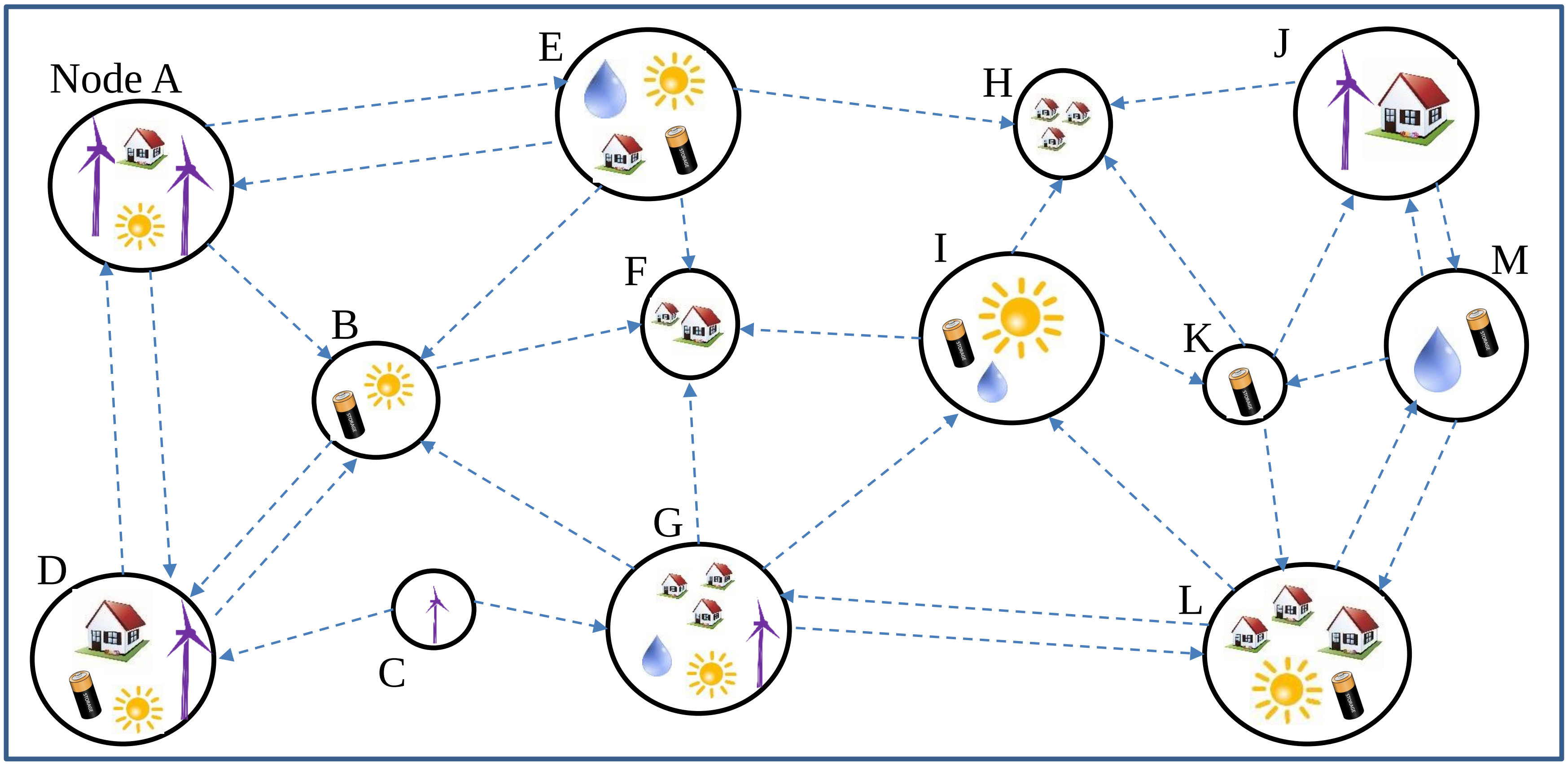
-Centralization to Decentralization





Source: http://energy.gov/sites/prod/files/oeprod/DocumentsandMedia/DOE_SG_Book_Single_Pages(1).pdf

-Centralization to Decentralization



Motivation

-Smart Grid

- Two way communication between customers and utility
- Consumer engagement
- More efficient transmission of electricity
- Reduced operations and management costs for utilities, and ultimately lower power costs for consumers
- Reduced peak demand, which will also help lower electricity rates

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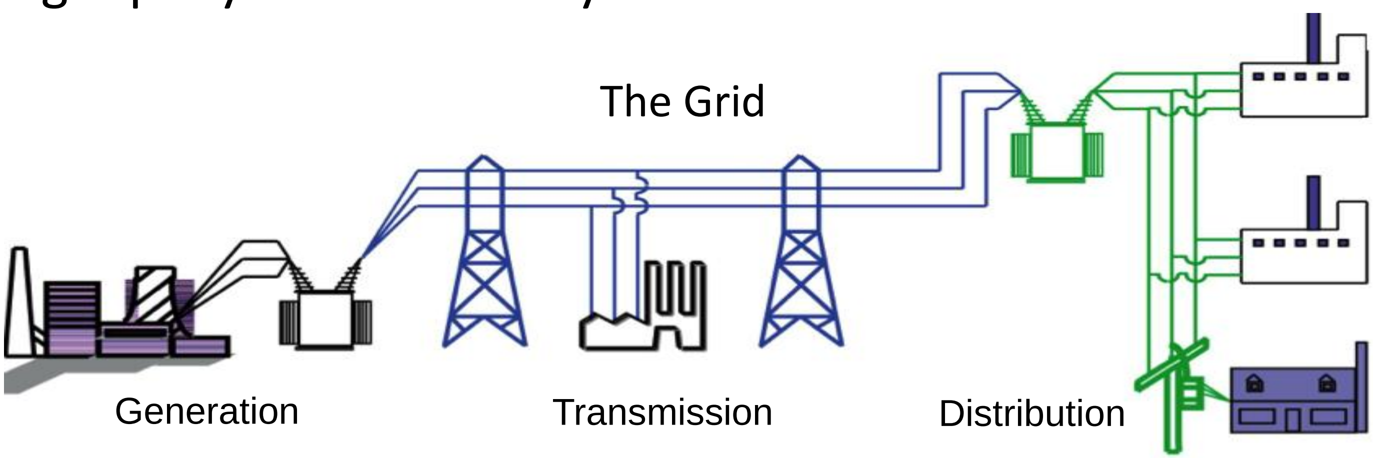
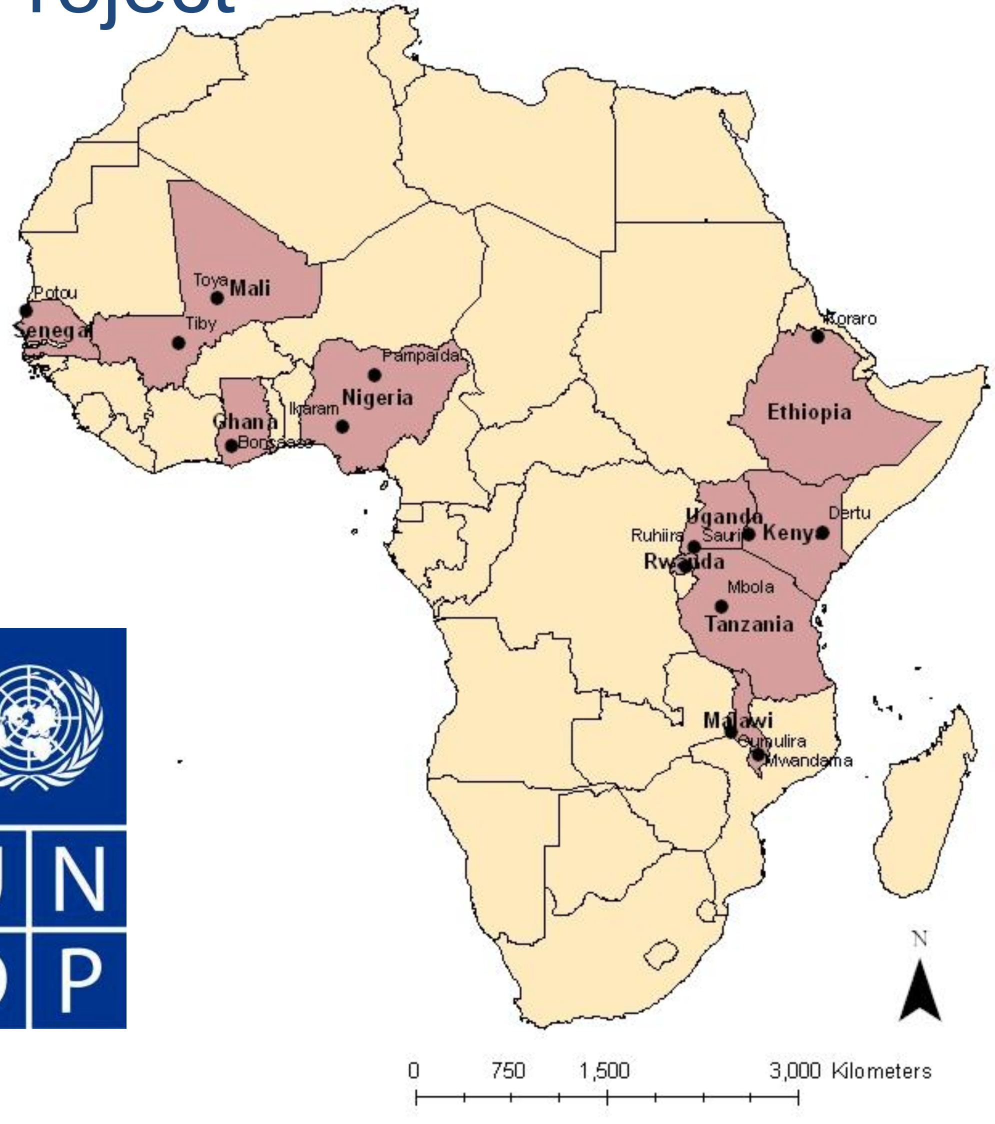


Energy Leapfrogging

Millennium Villages Project

-Focuses on empowering villages through public investments to develop critical infrastructure and social capital needed for achieving the United Nations **Millennium Development Goals**



Off-Grid vs. Grid Electrification ?

Distributed or Networked Infrastructure ?

Solar

Wind

Micro-Diesel

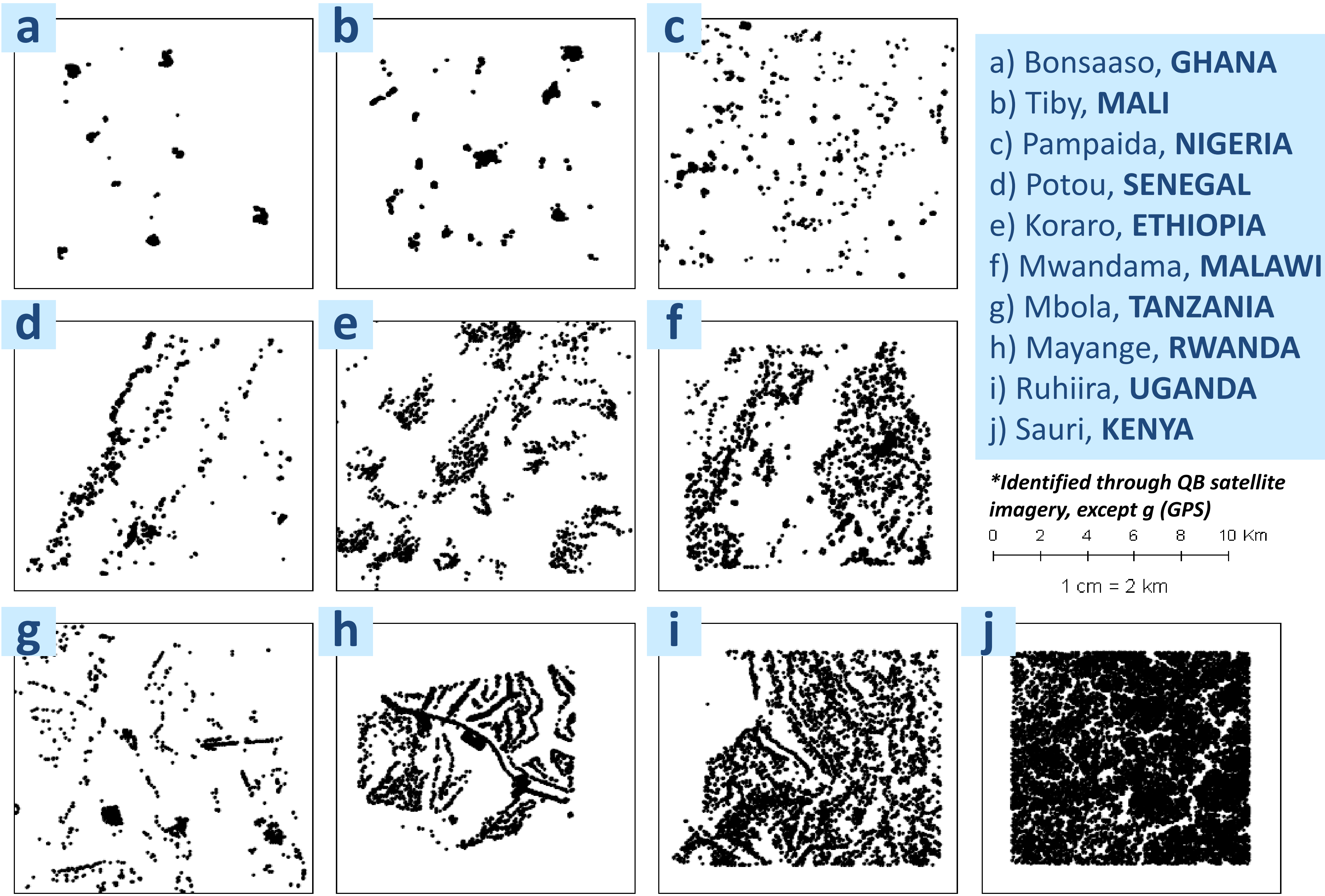
Micro-Hydro

Grid

Ruhiira, Uganda

Where do people live?

Where do people live?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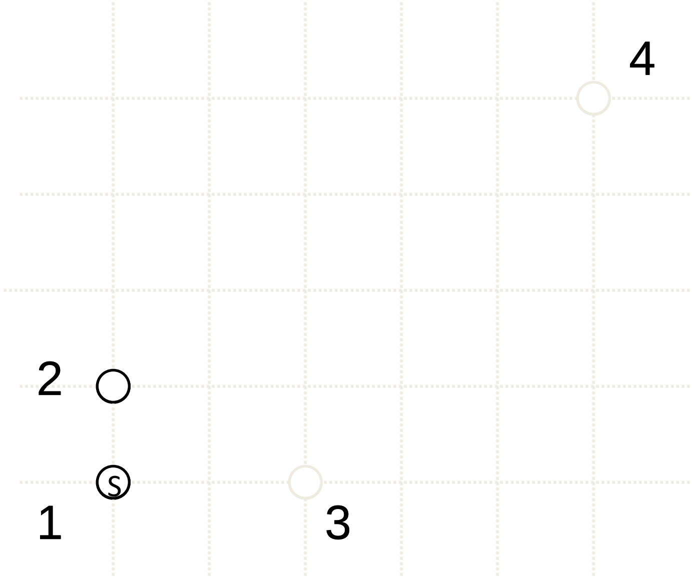
a) Bonsaaso, **GHANA**
b) Tiby, **MALI**
c) Pampaida, **NIGERIA**
d) Potou, **SENEGAL**
e) Koraro, **ETHIOPIA**
f) Mwandama, **MALAWI**
g) Mbola, **TANZANIA**
h) Mayange, **RWANDA**
i) Ruhiira, **UGANDA**
j) Sauri, **KENYA**
Identified through QB satellite imagery, except g (GPS)
0 2 4 6 8 10 Km
1 cm = 2 km

Single Level Electrification-Problem Statement
(Only Low Voltage Wire)

- Full Connectivity
  - What is the cost of connecting each household to electricity?



Minimum Spanning Tree

Prim's Algorithm (1957)

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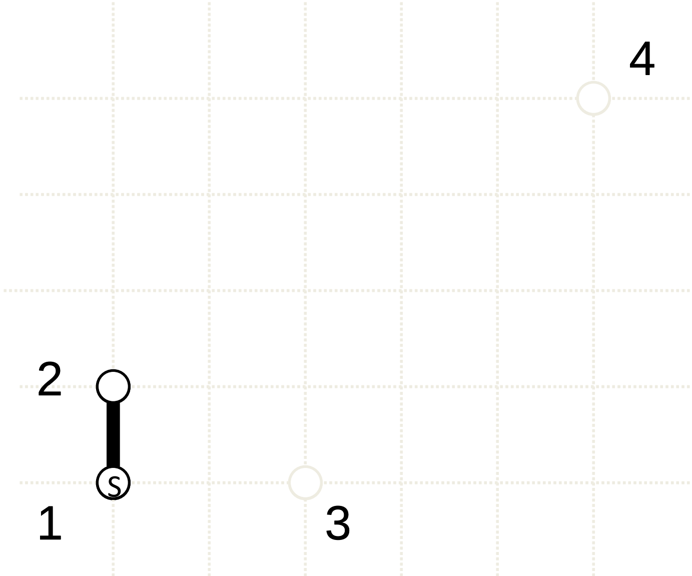

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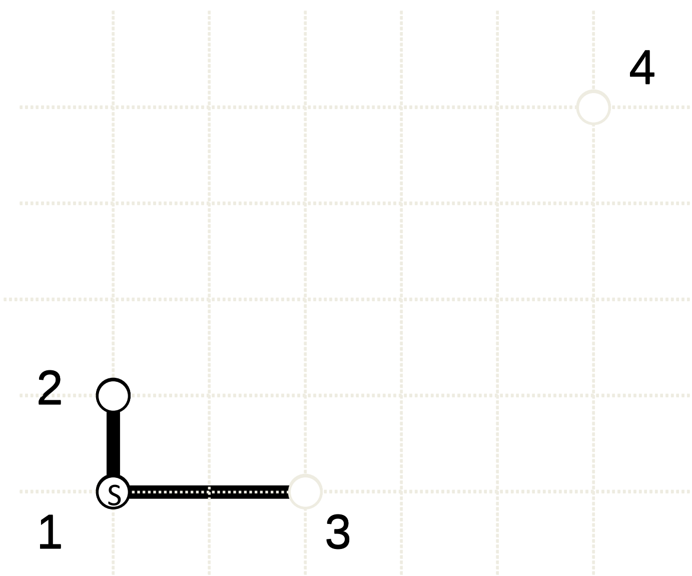

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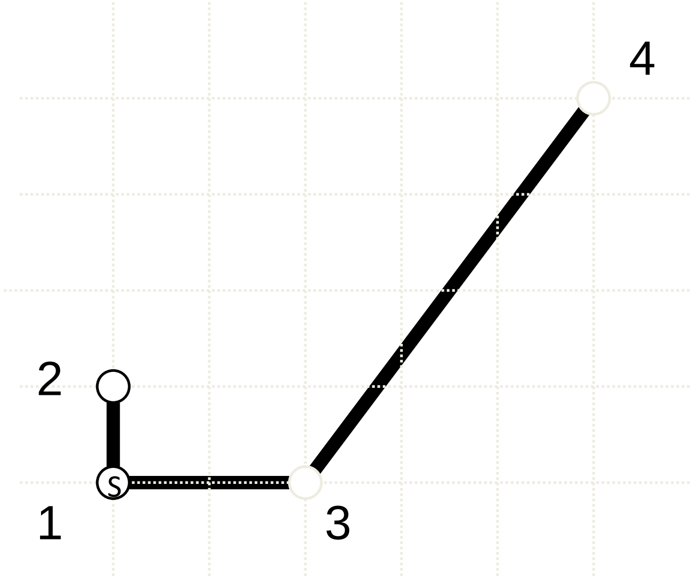


Total length of the network: 8

Average length of the segments in the MST: 8/3

Mean Interhousehold Distance (MID) →8/3

Single Level Electrification-Problem Statement
(Only Low Voltage Wire)

- Full Connectivity
  - What is the cost of connecting each household to electricity?

- Partial Connectivity
  - The partial electrification problem:

Find: A network such that the mean interhousehold distance (MID) is minimized

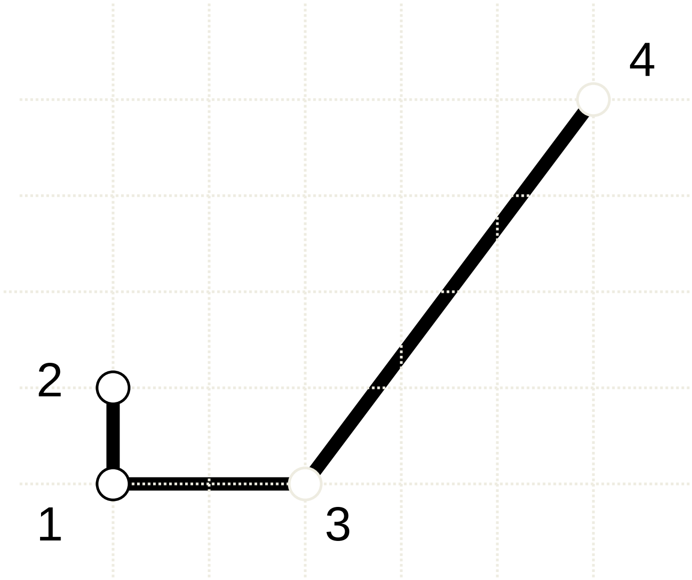
Subject to: The network connects a pre-specified percentage of the households

  - How does the per-unit cost of grid construction vary with penetration rate?
  - How does rural population structure affect the cost of infrastructure investments?

Partial Electrification (p% connectivity):

When p= 100% (full penetration rate):

- MST is the optimal solution
- Independent of the starting point



For p<100%:

- Dependent on the starting point
- k-MST Problem (NP-Hard)

Partial Electrification (p% connectivity):

When p= 100% (full penetration rate):

- MST is the optimal solution
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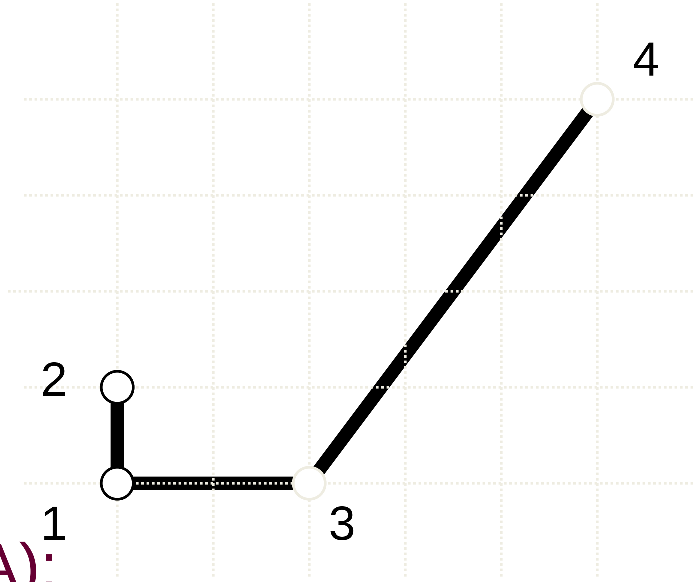
For p<100%:

- Dependent on the starting point
- k-MST Problem (NP-Hard)



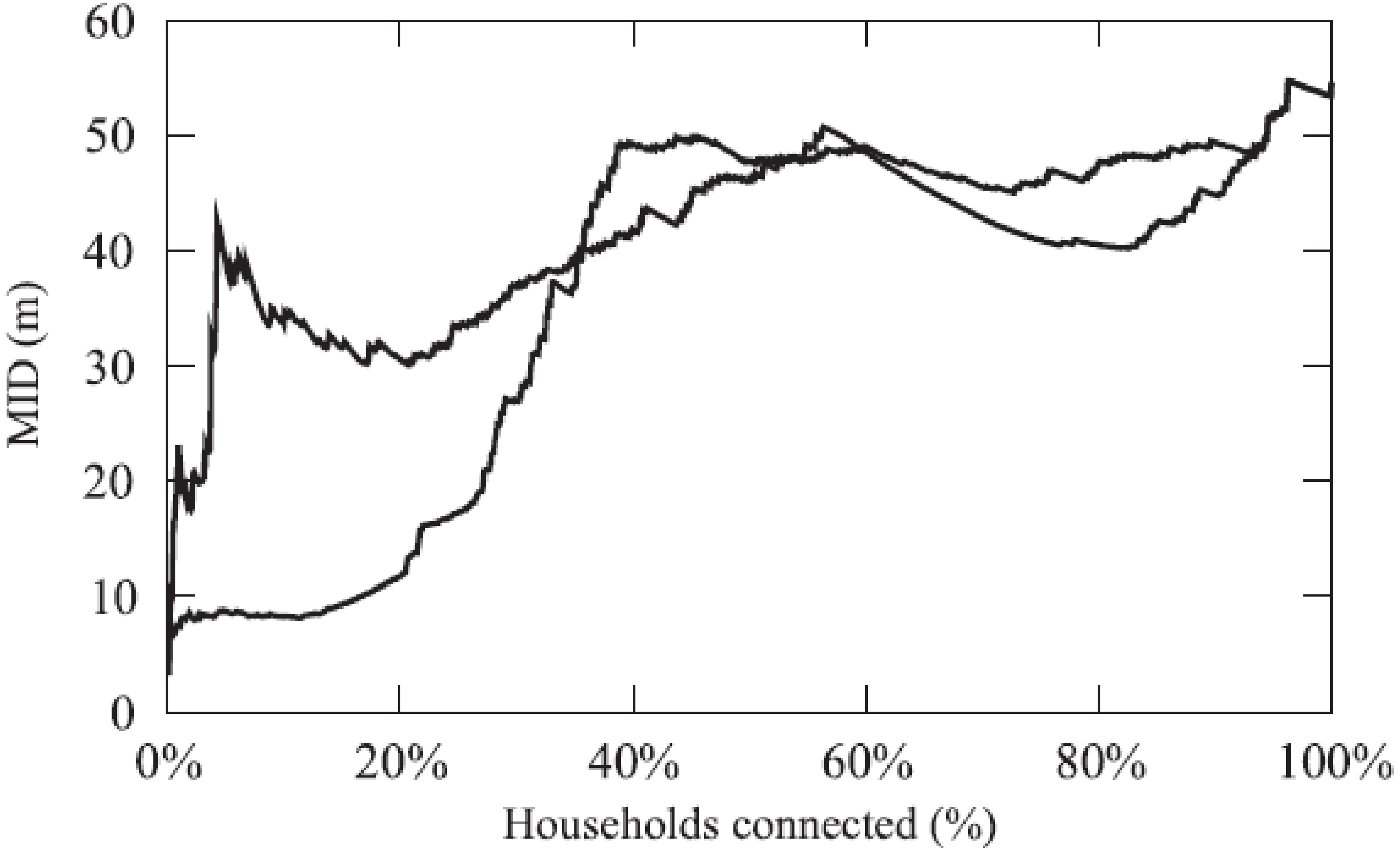
Composite Prim's Algorithm (CPA):

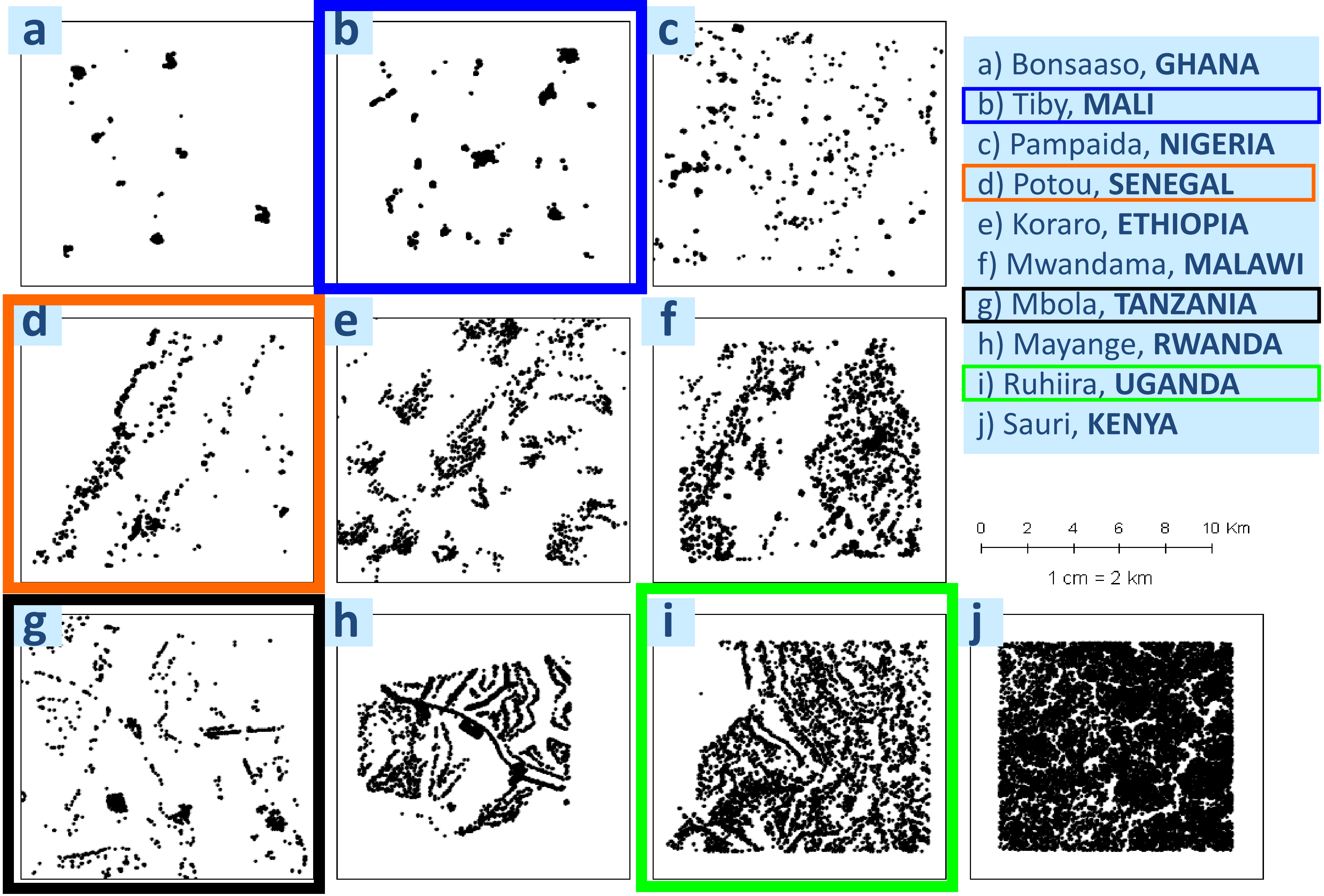
– Run Prim's Algorithm repeatedly until the given penetration rate is achieved for each starting point.

– For each penetration rate, select the network which has minimum MID

Results of CPA for two starting points

-Potou, SENEGAL

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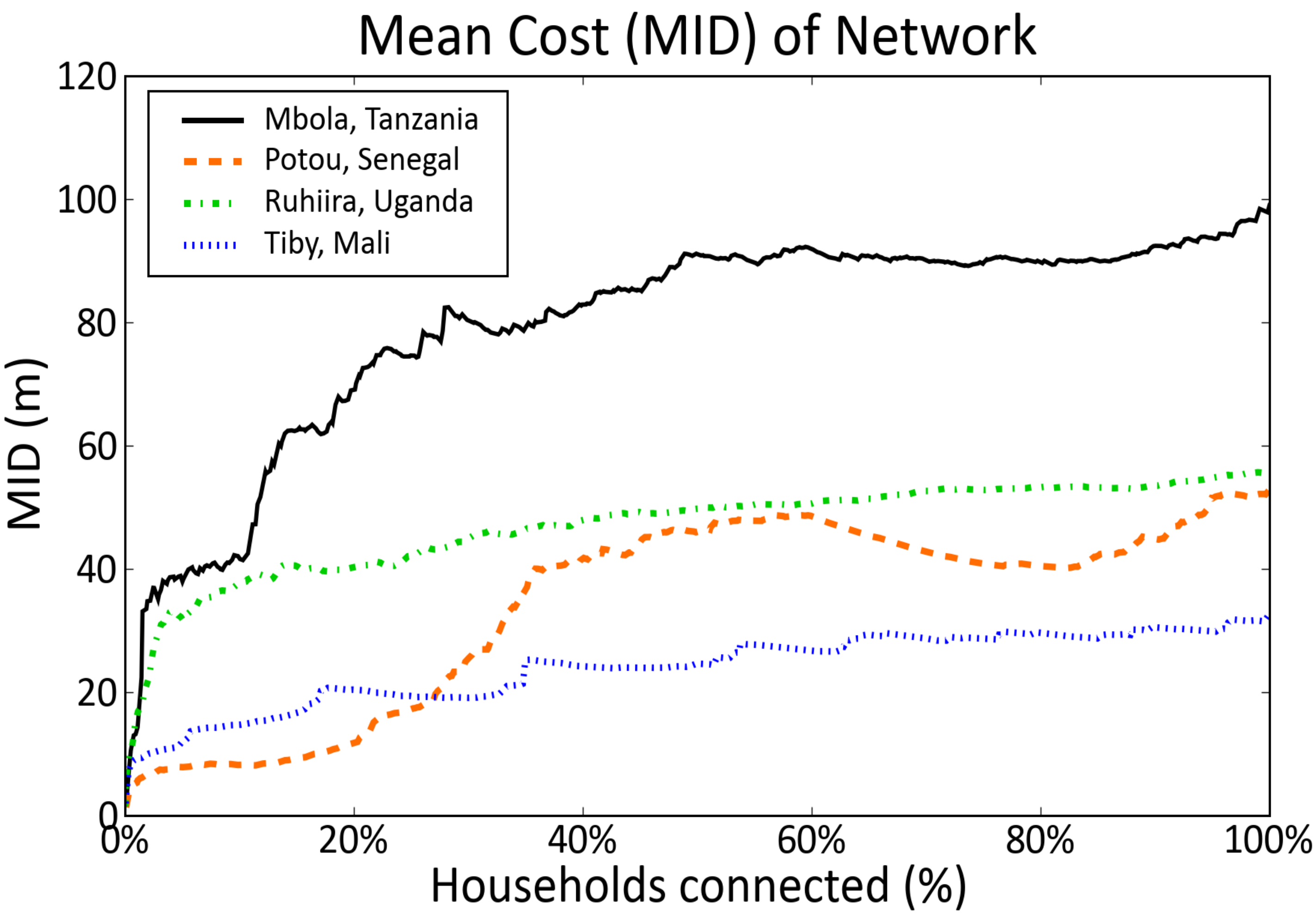
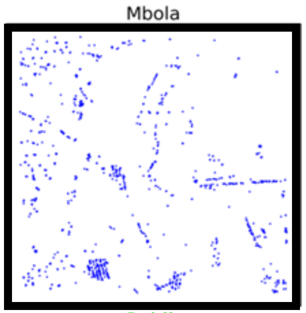
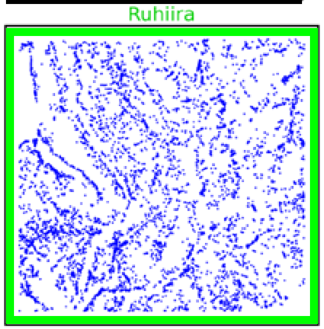
0 2 4 6 8 10 Km
1 cm = 2 km

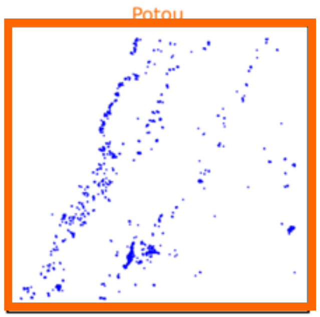
Mean Cost Calculations (MID)

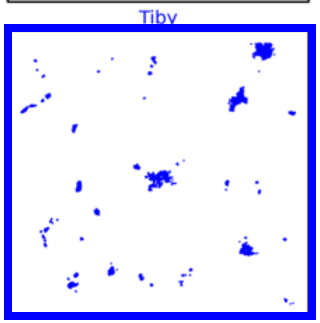
Results for Different Dispersion of Structures











Multi-level Electrification*

(Low Voltage (LV) and Medium Voltage (MV) Wires)

Power Distribution System Design Problem

Given :

–Demand Point Locations

–Cost Parameters

- C_{MV} :Cost of 1m MV wire
- C_{LV} :Cost of 1m LV wire
- C_{T} :Cost of one transformer

*A.S. Kocaman, W.T. Huh, Modi, V. Applied Energy, Smart Grid Special Issue, 2012

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- C_T :Cost of one transformer

Subject to:

–D_{max}: The maximum direct distance between a demand point and transformer

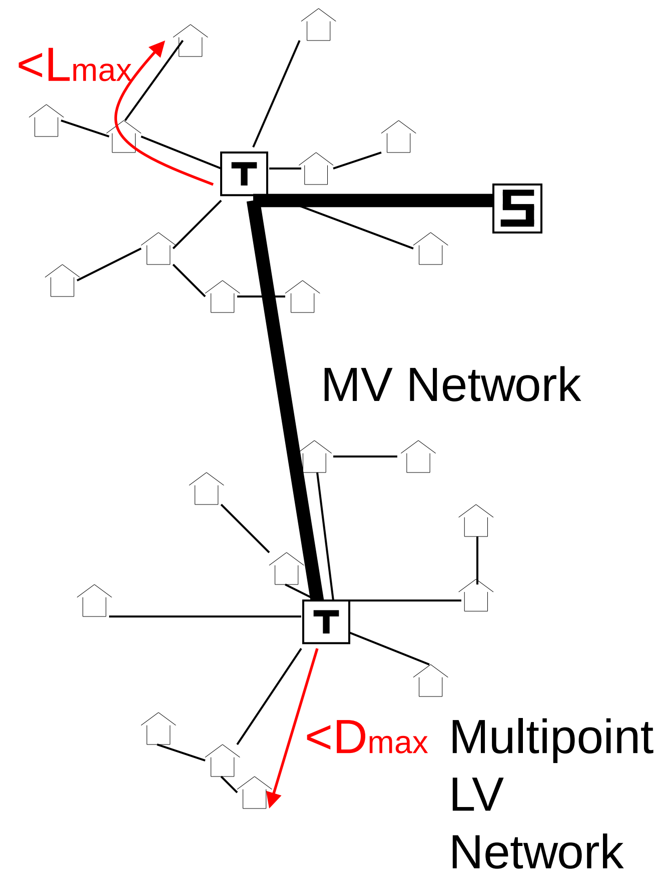
–L_{max}: The maximum distance capacity of LV wire

Find:

–The number and locations of the transformers

–Medium voltage network between a source point and transformers

–Multipoint low voltage network between transformers and their associated demand points



*A.S. Kocaman, W.T. Huh, Modi, V. Applied Energy, Smart Grid Special Issue, 2012

Multi-level Electrification- Solution Methodology

(Power Distribution System Design)

- Initialize one transformer for each demand point
- Repeat iterations below until no further change can be made
  - Search for a pair of two closest transformers
  - Remove these transformers and add a new transformer in the center of mass of the demand points if the resulting network does not violate Dmax.

  Agglomerative Hierarchical Clustering

  - Build a medium voltage network between transformers and the source point

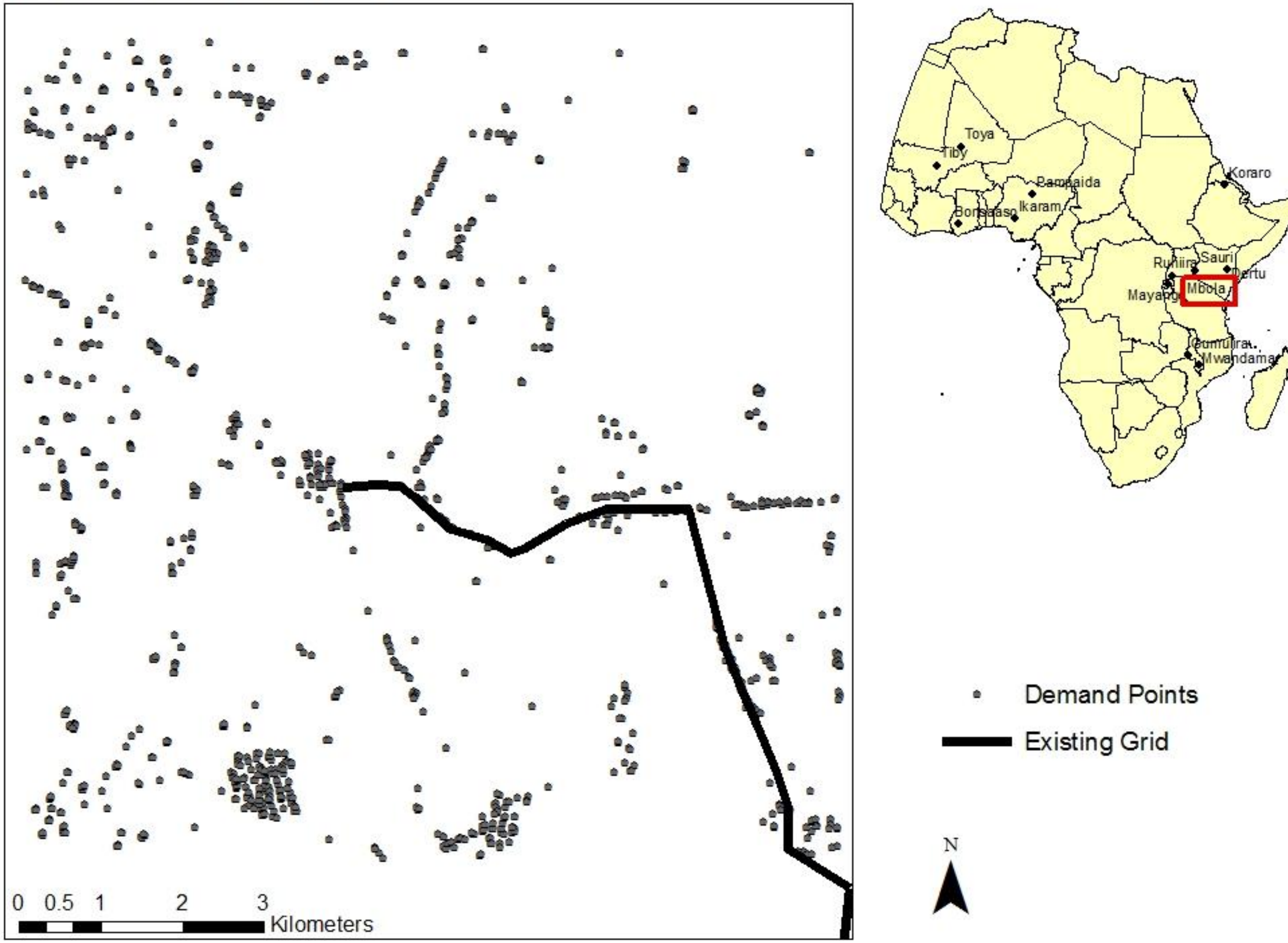
  Minimum Spanning Tree

  - Build a low voltage network between transformers and their associated demand points
  - Record the total cost of the design

  Capacitated Minimum Spanning Tree

- Compare the recorded costs and select the most cost efficient design

Mbola, TANZANIA



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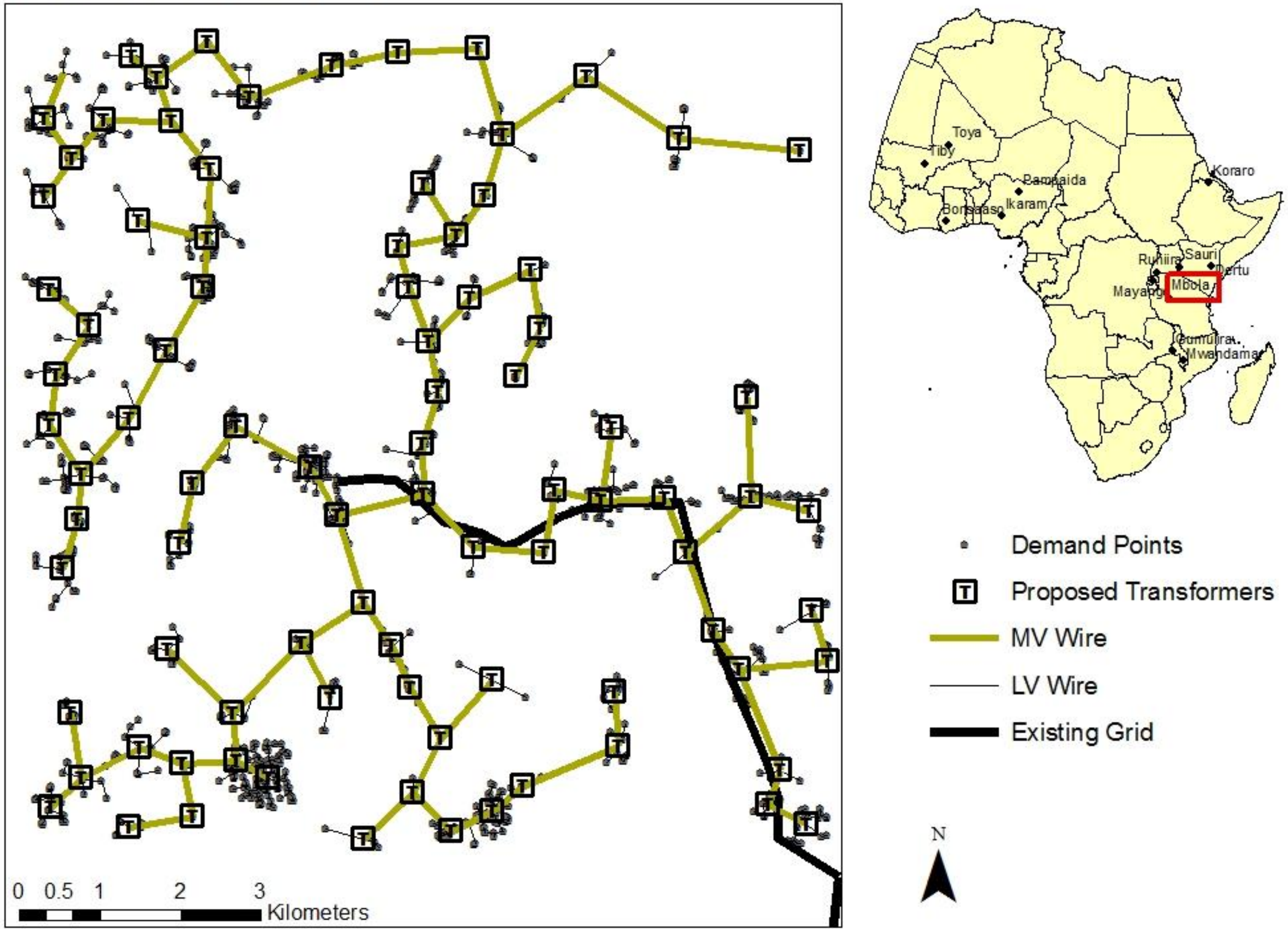

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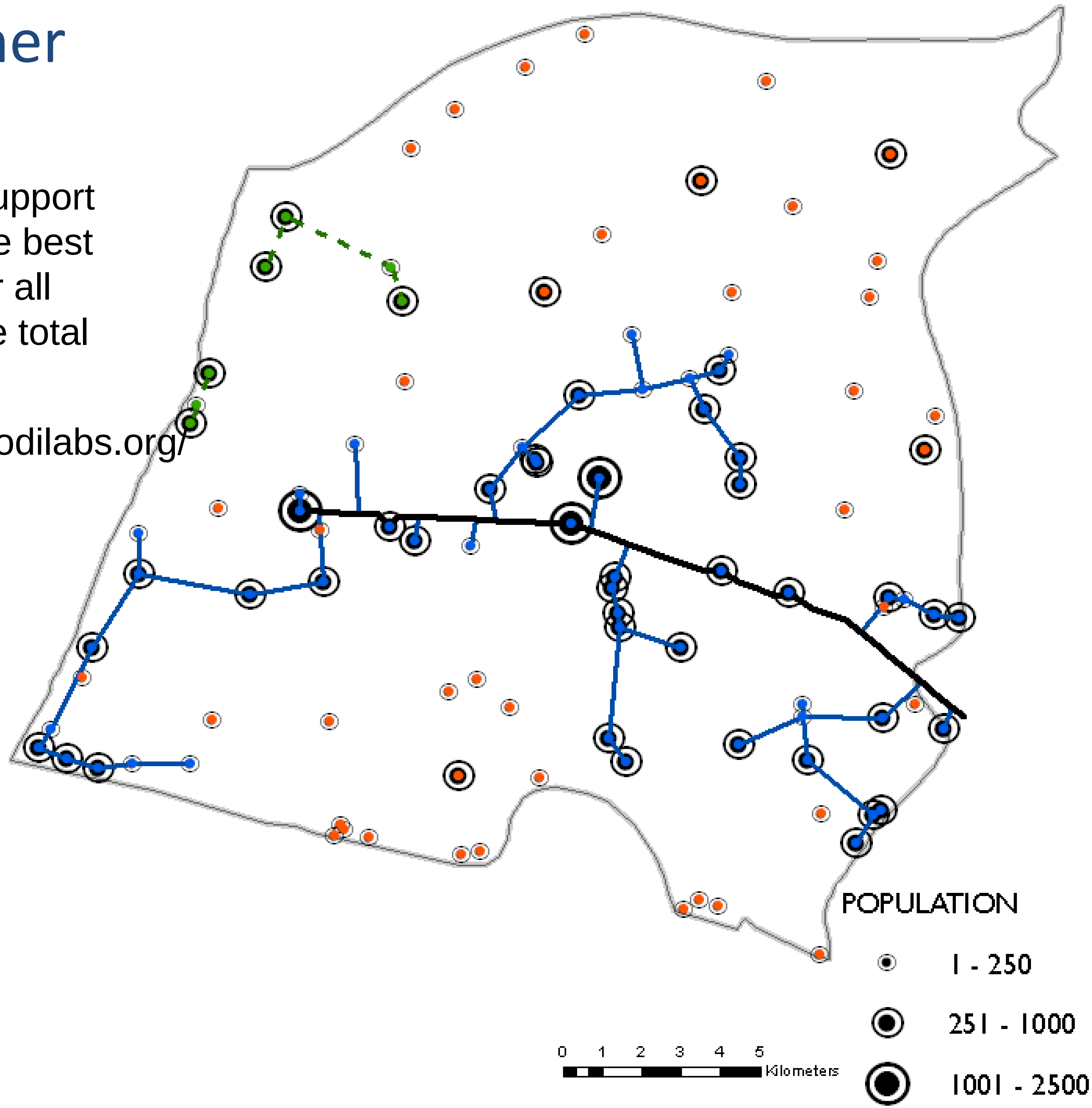
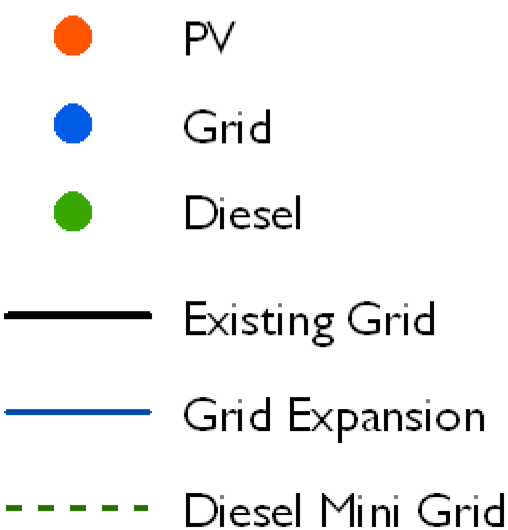
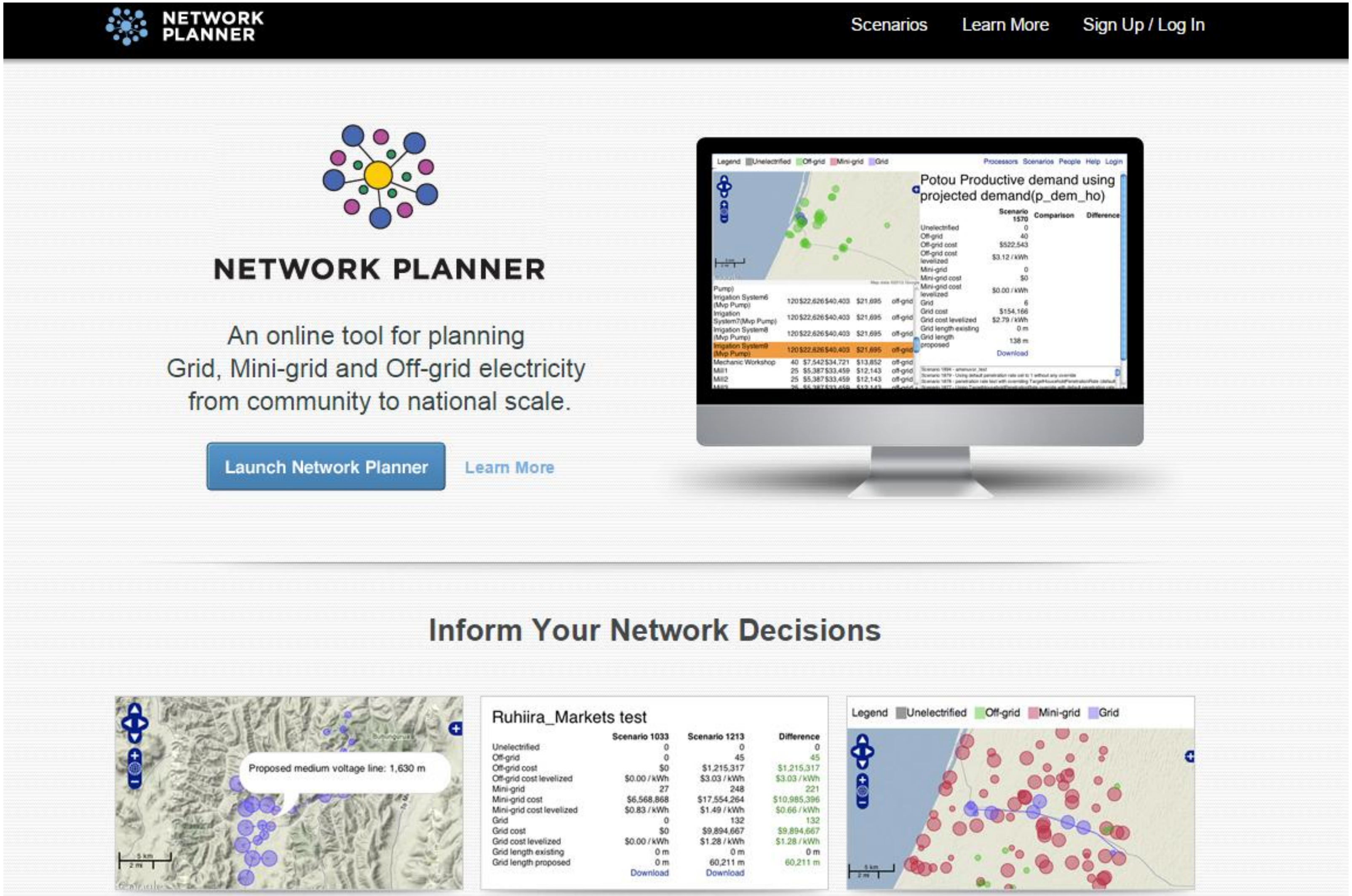
Network Planner

An online decision support tool which selects the best technology option for all nodes minimizing the total cost of the system

http://networkplanner.modilabs.org/



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Inform Your Network Decisions
Proposed medium voltage line: 1,630 m
Ruhiira_Markets test
Scenario 1033 Scenario 1213 Difference
Unelectrified 0 0 0
Off-grid 0 45 45
Off-grid cost $0 $1,215,317 $1,215,317
Off-grid cost levelized $0.00 / kWh $3.03 / kWh $3.03 / kWh
Mini-grid 27 248 221
Mini-grid cost $6,568,868 $17,554,264 $10,985,396
Mini-grid cost levelized $0.83 / kWh $1.49 / kWh $0.66 / kWh
Grid 0 132 132
Grid cost $0 $9,894,667 $9,894,667
Grid cost levelized $0.00 / kWh $1.28 / kWh $1.28 / kWh
Grid length existing 0 m 0 m 0 m
Grid length proposed 0 m 60,211 m 60,211 m
Download Download
Legend Unelectrified Off-grid Mini-grid Grid

- Used for national electrification projects in Kenya, Senegal, Ghana, Nigeria, **Myanmar**

REUTERS AFRICA

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World Bank approves $400m loan for Myanmar's power plan

Thu Sep 17, 2015 9:52am GMT

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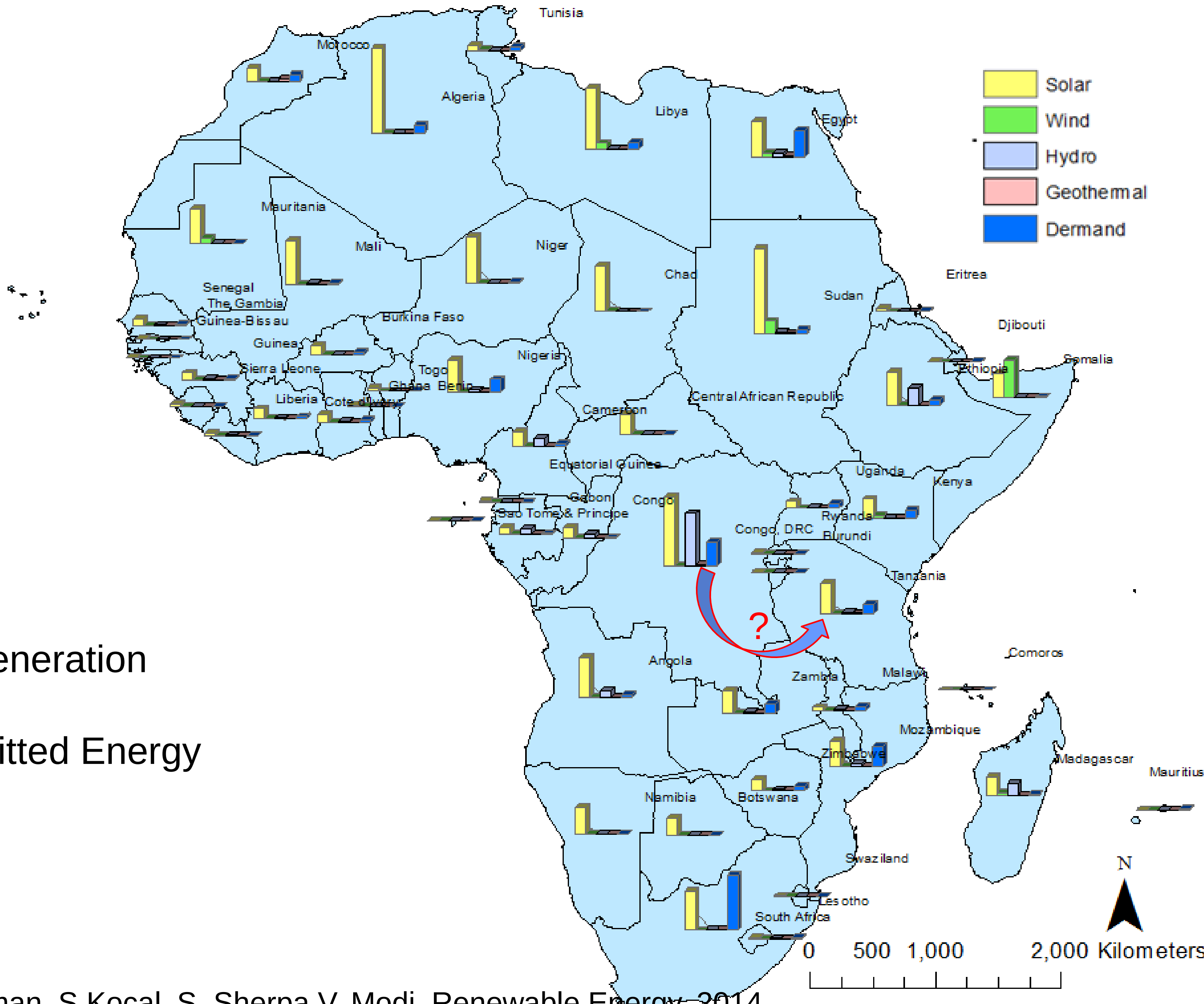
YANGON, Sept 17 (Reuters) - The World Bank has approved $400 million in interest-free credit to support Myanmar's moves to boost electricity access across one of Asia's poorest and least-connected countries.

Ideal Energy Distribution in Africa



Own Generation
vs.
Transmitted Energy

*A. Sanoh, A.S. Kocaman, S.Kocal, S. Sherpa,V. Modi. Renewable Energy, 2014

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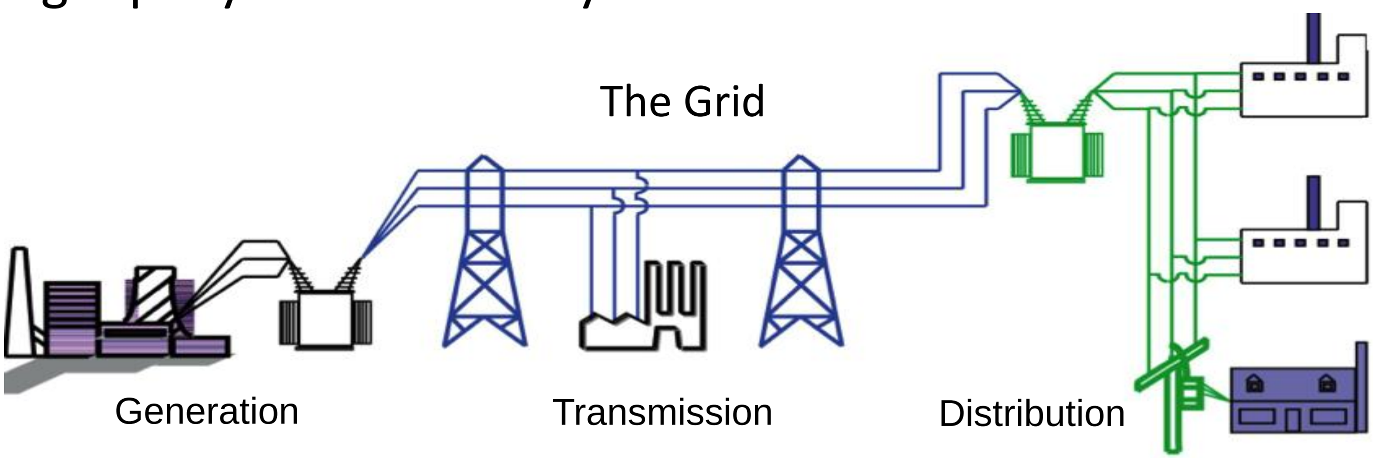
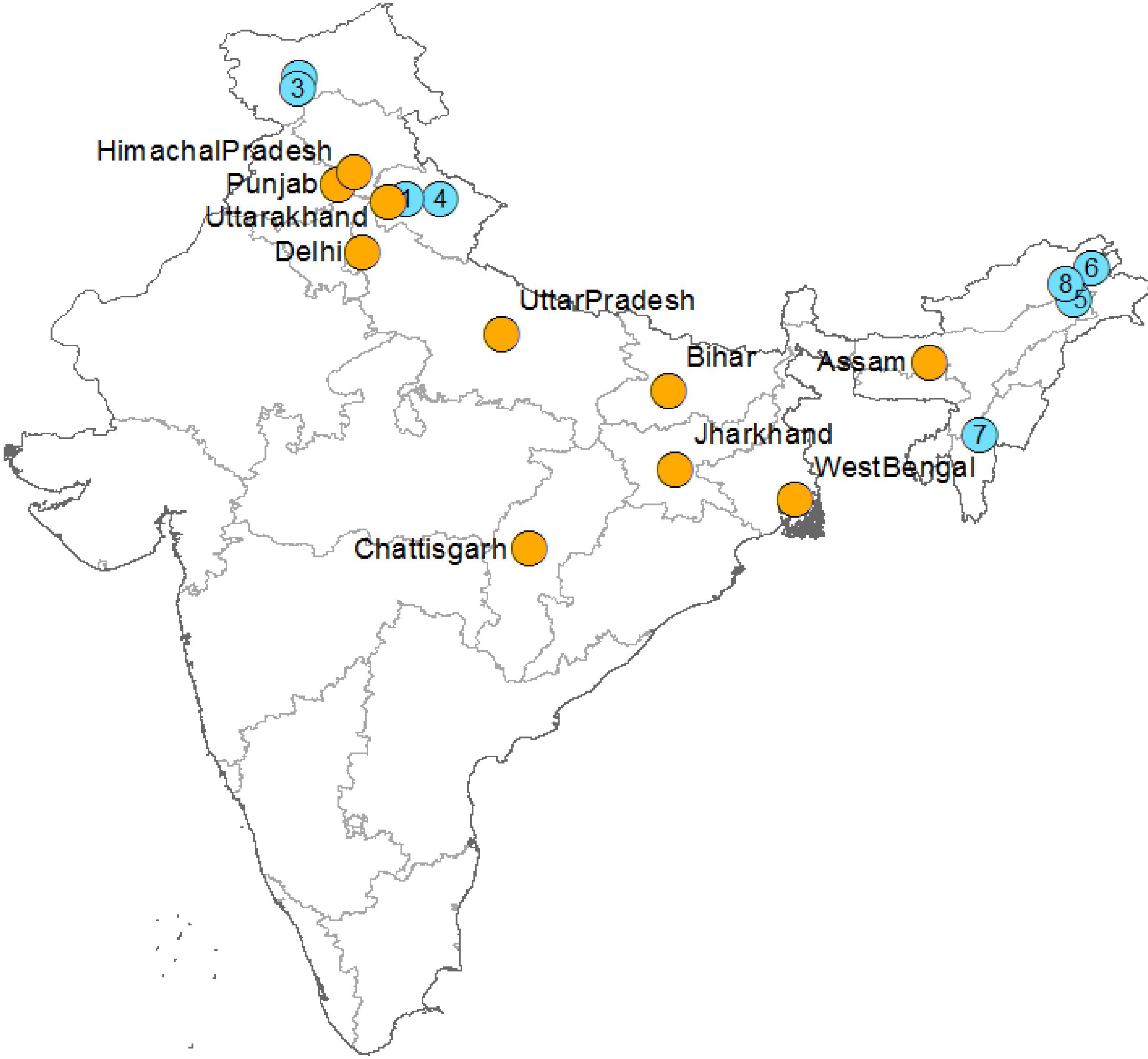


Towards a Low-Carbon Economy
-Integration of Renewables

- To address the challenges of renewables:
  - ***Intermittency*** : Limited controllable variability and partial predictability
  - ***Spatial Location*** :Location mismatch between potential of renewable energy generation and where the energy will be ultimately consumed

- with the technologies for grid integration of renewables
  - ***Hybrid Systems*** operate as a combination of alternative renewable sources to increase reliability and decrease storage costs
  - ***Energy Storage*** balances supply and demand
  - ***Long Distance Transmission*** (geographic aggregation) smoothes the variability of the intermittency of wind and solar energy over large distances
  - ***Demand Response Programs***

Mathematical Modeling of a Hybrid Energy Generation and Allocation System



We imagine a country in the future where **hydro** and **solar** are the dominant sources and fossil fuels are only available as a back-up source.

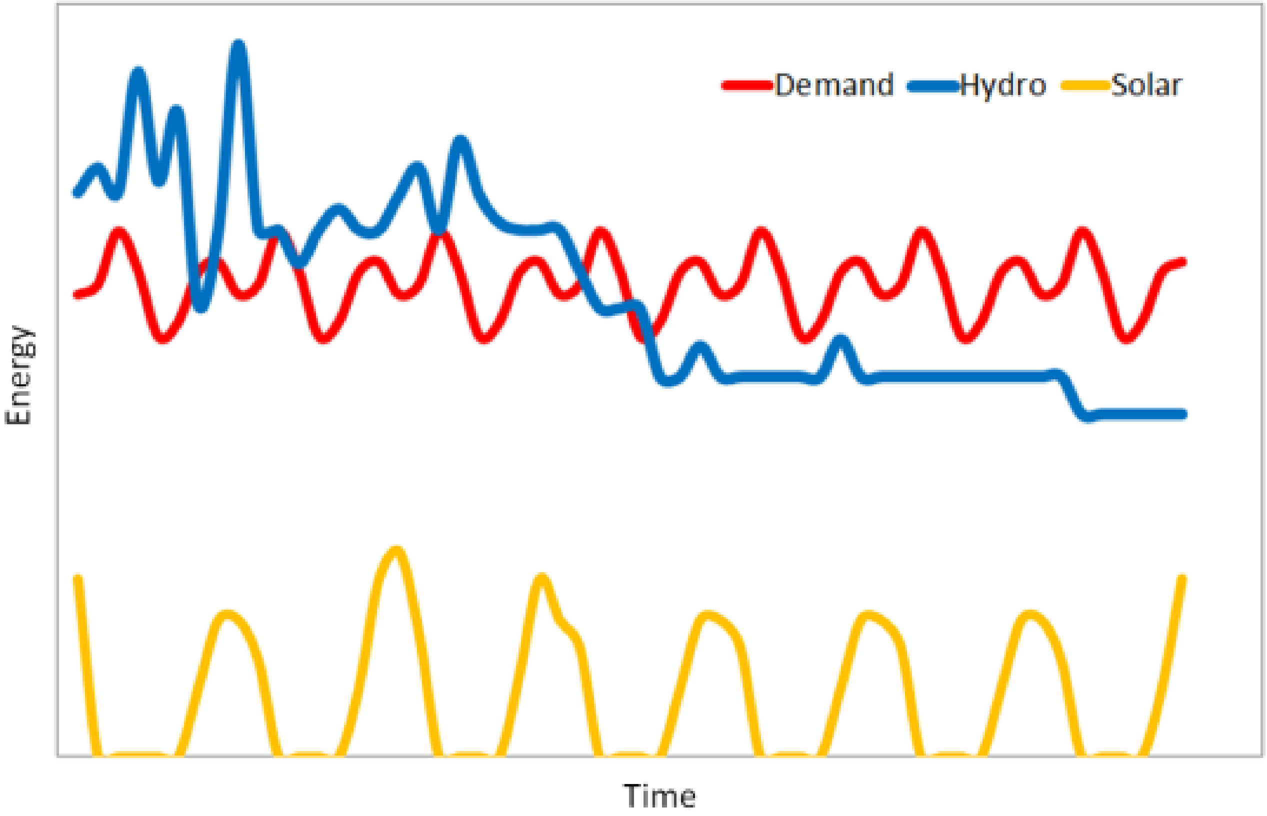
In this country, we identify candidate basins for hydro power stations and aggregated demand point locations such as the cities or the states of the country in which solar energy production is possible.

We mathematically model this hybrid energy **generation** and **allocation** system, where time variability of energy sources and demand is balanced with **conventional** and/or **pumped hydro storage.**

A. Selin Kocaman et al. / Renewable and Sustainable Energy Reviews 54 (2016) 688–703

Problem Statement

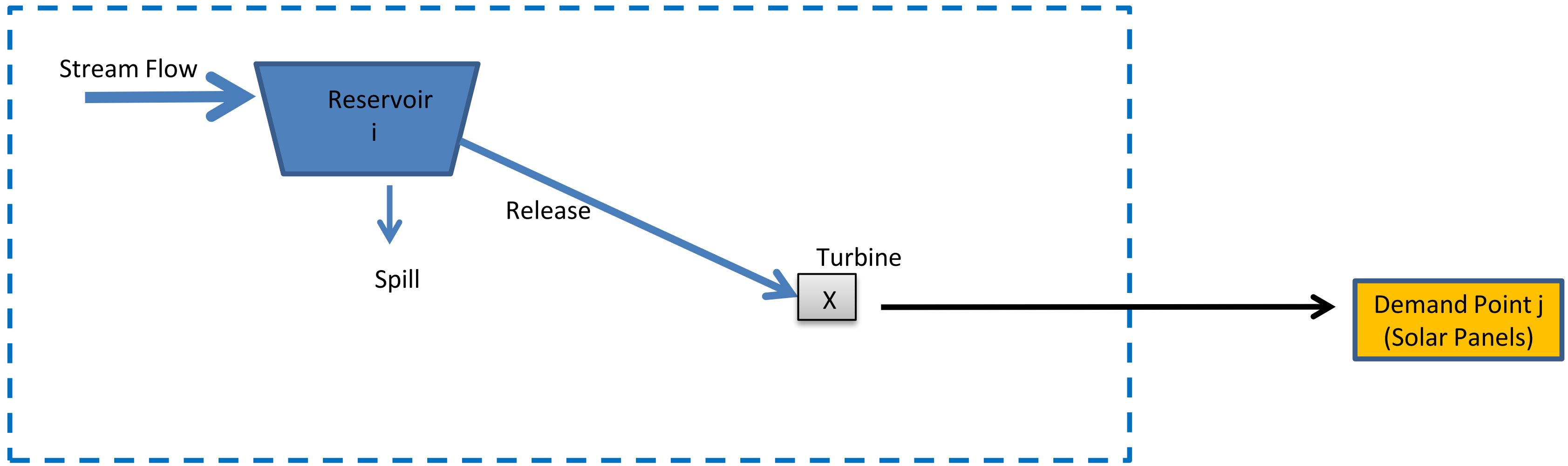
-Variability of Supply and Demand



Problem Statement

-Hybrid Energy System with Hydro Storage

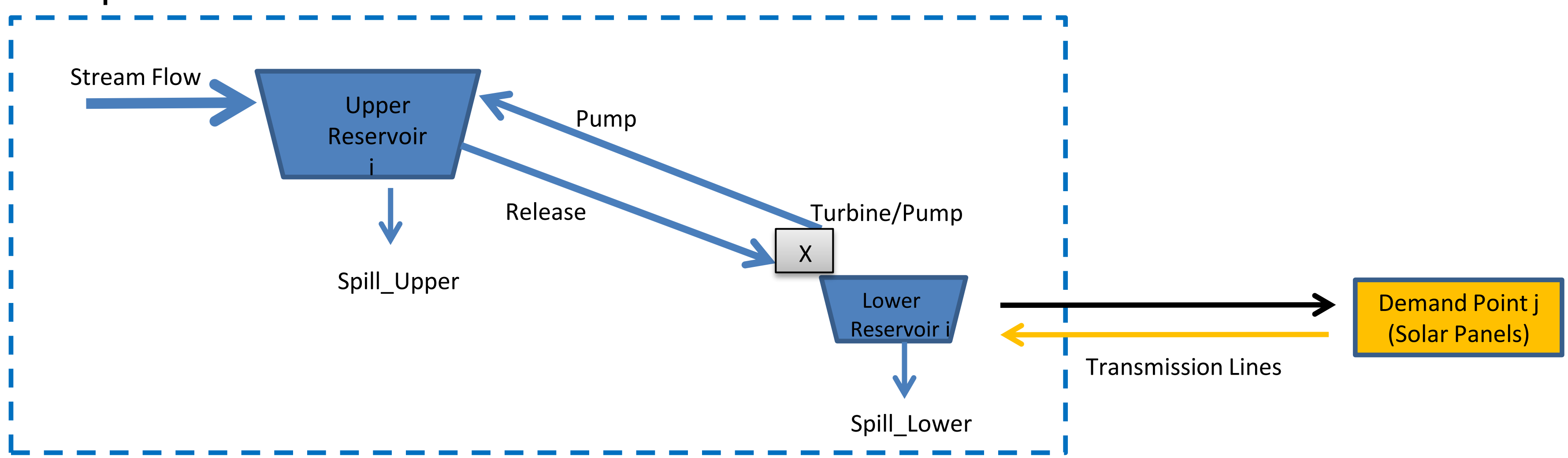
-Conventional



i: Candidate locations for hydropower stations

j: Demand point locations

-Pumped



Problem Statement

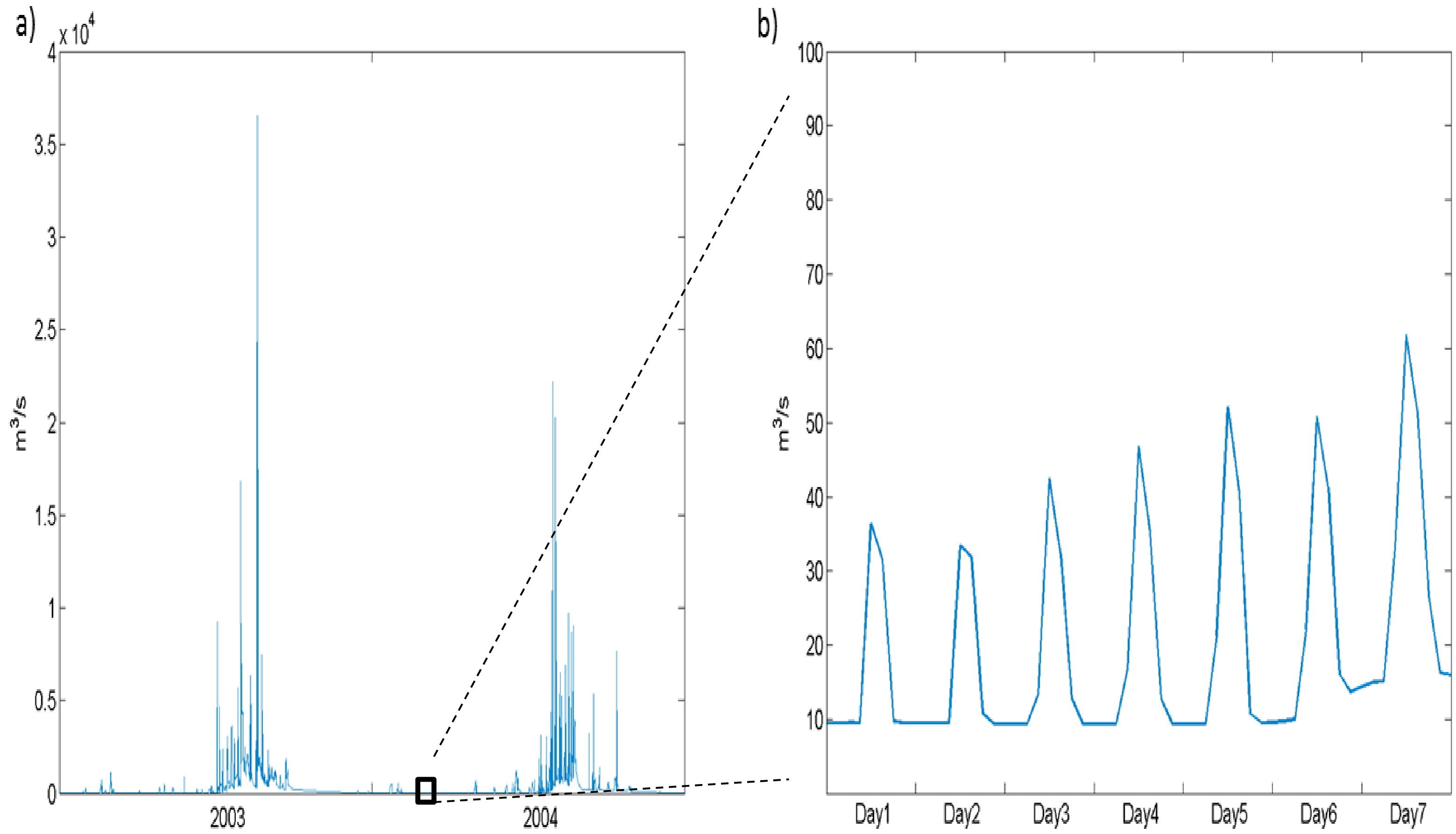
Given time series data for stream flows, solar radiation and projected demand, we want to investigate:

- where, when and how much solar and hydro energy should be produced at each time unit? ⇒ Hybrid Systems
- what should be the size of reservoirs so that the demand and supply would be matched? ⇒ Energy Storage
- from /to where and how much energy should be transmitted? ⇒ Transmission

to meet the projected demand!

Input Data - Stream Flow

- 3-hourly stream flow data for the years between 1951 and 2004 for each candidate basins is obtained from the Variable Infiltration Capacity (VIC) land surface model (Liang et al. 1994,1996)

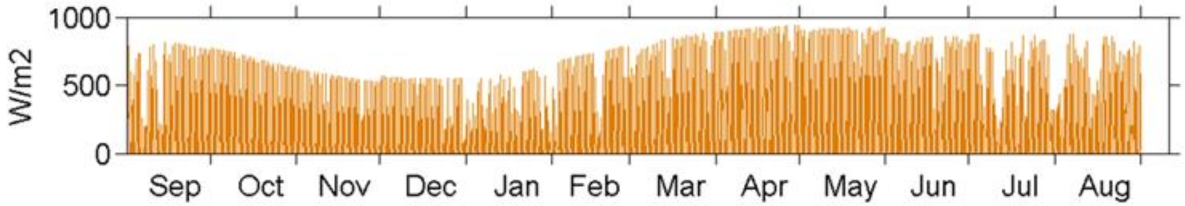


a, Stream Flow Data of Bhagirathi River for 2003 and 2004. Monsoon is expected to be observed around June and its withdrawal completes by around October every year. **b,** Stream Flow Data of Bhagirathi River for a week in March. Most of the snow melts occur in the summer period correlated with the sun light and cause diurnal variation in the stream flow.

Input Data - Solar Radiation

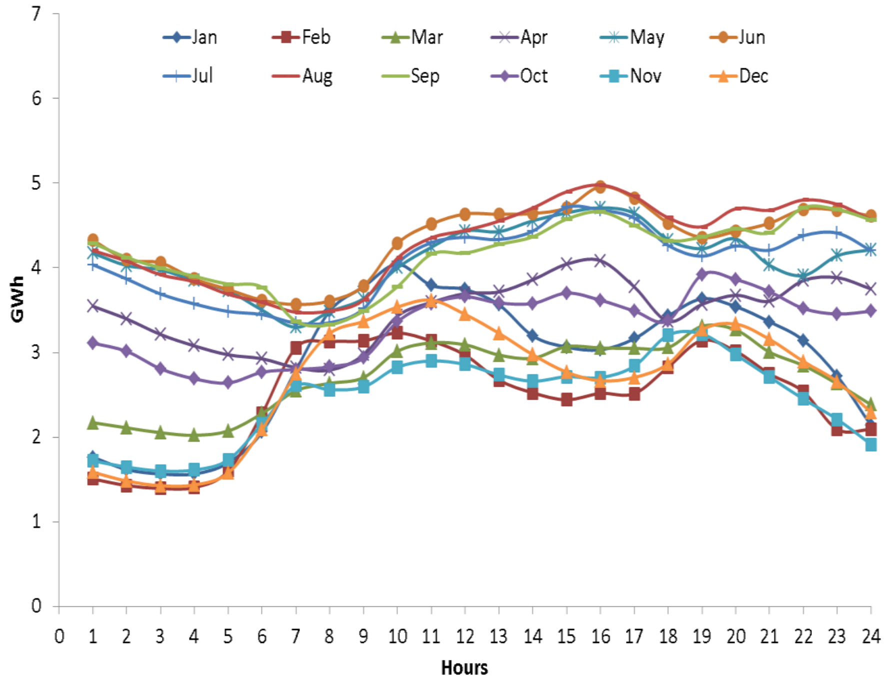
- Site and time specific, high resolution solar radiation data was developed using weather satellite by the U.S. National Renewable Energy Laboratory (NREL) in cooperation with India's Ministry of New and Renewable Energy. Global and direct irradiance at hourly intervals on the 10-km grid for all of India for the years 2001-2008 is available on NREL's website.

			Period 2001-2008 (Global Horizontal Irradiance : W /m2)				
	Lat (°E)	Long (°N)	Min	Max	Average	Standard Deviation	Coefficient of Variation
Delhi	29.02	77.38	0	1004	213	295	1.38
Punjab	30.79	76.78	0	980	208	287	1.38
Uttaranchal	30.33	78.06	0	998	209	289	1.38
HimachalPradesh	31.10	77.17	0	1013	213	292	1.37
UttarPradesh	26.85	80.91	0	1002	221	320	1.45
Bihar	25.37	85.13	0	1006	221	321	1.45
WestBengal	22.57	88.37	0	999	212	313	1.47
Jharkhand	23.35	85.33	0	1009	224	224	1.00
Assam	26.14	91.77	0	974	193	273	1.41
Chattisgarh	21.27	81.60	0	1003	232	312	1.34

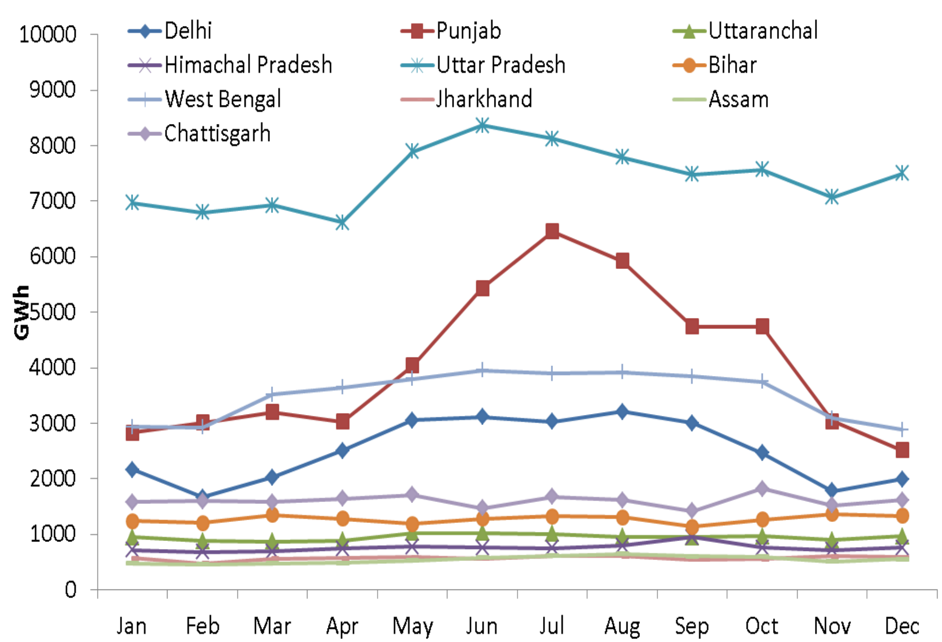


Input Data - Demand

- Total monthly power availabilities and requirements for each state for the year 2012 are provided on Central Electricity Authority, Power Ministry of India (CEA) website.
- On the websites of Load Dispatch Center of Delhi, Chhattisgarh, Assam and Punjab daily, weekly or monthly reports for daily load profiles for a number of days or for the times when the minimum and maximum demands are presented.
- We have used the collected data to accurately estimate the 3-hourly demand load profile of each state for one year using interpolation/extrapolation methods.

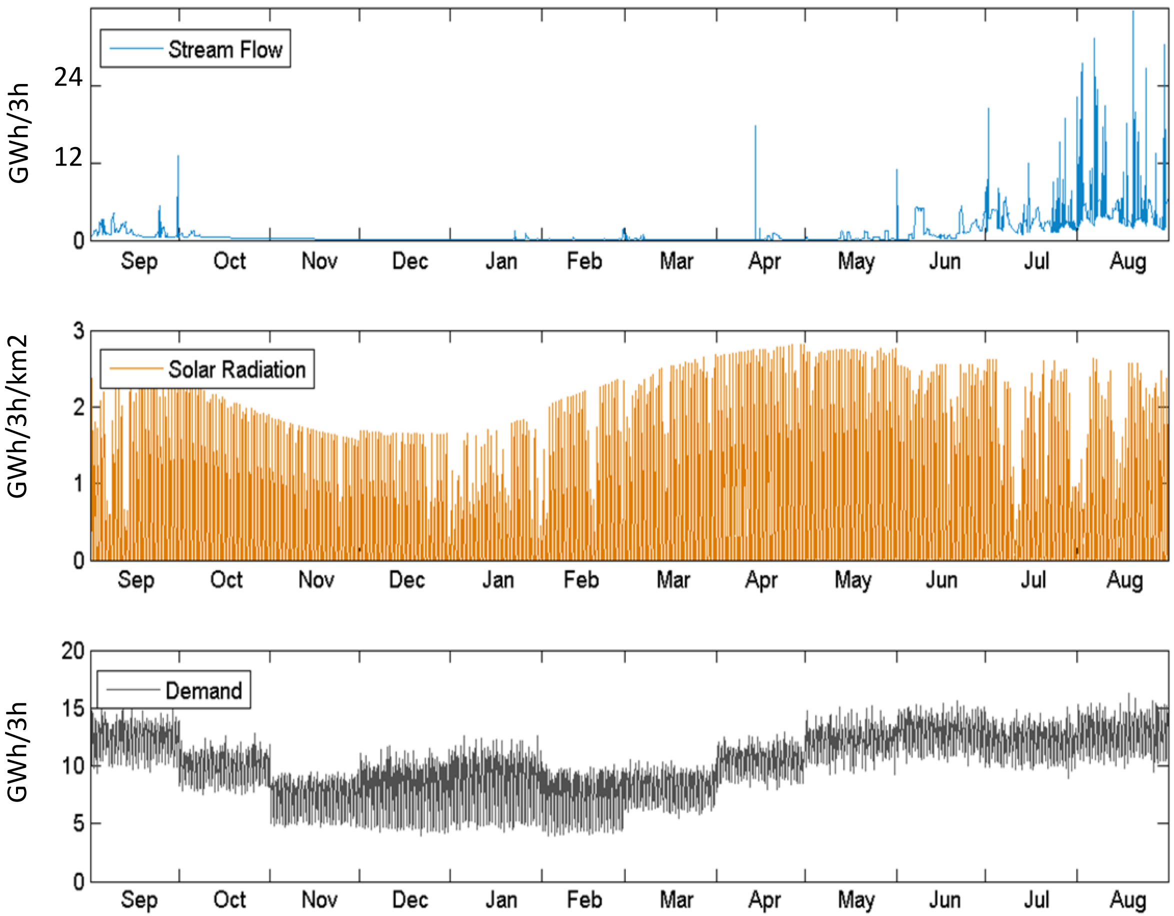


Daily demand profile of Delhi in 2012



Monthly total demand of ten states in India in 2012

-Input Data for One Scenario

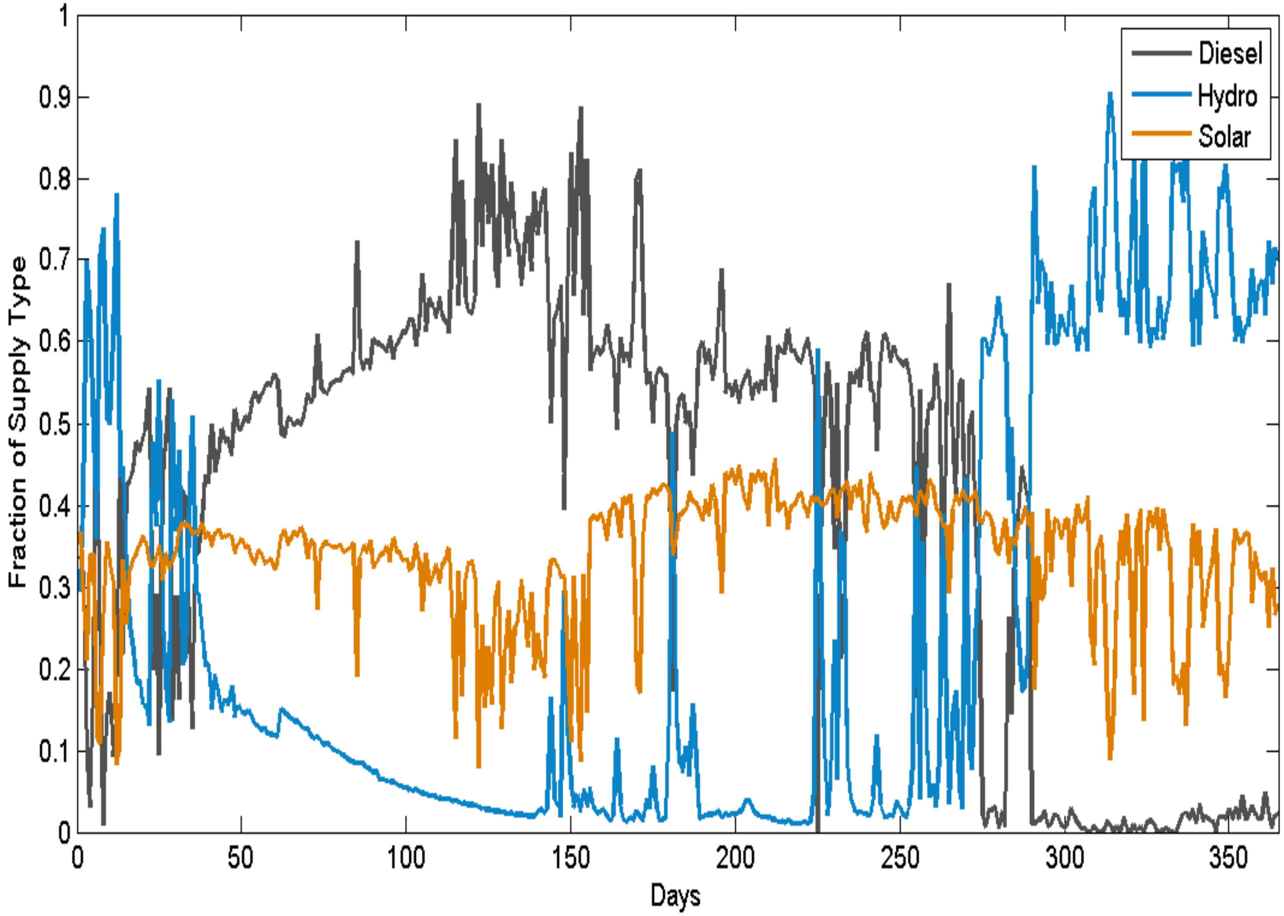


- Parameters

Unit Cost of Reservoir Capacity C_{Si}:	\$1/m3	Efficiency of Hydropower System α:	88%
Unit Cost of Generator Capacity C_{PGi}:	\$500/kW	Efficiency of Solar Panels γ:	12%
Unit Cost of Solar Array C_{Mj}:	\$150/m2	Discount Rate:	5%
Unit Cost of Diesel μj:	\$0.15/kWh	Planning Horizon:	25 years

Results- Conventional Hydro System

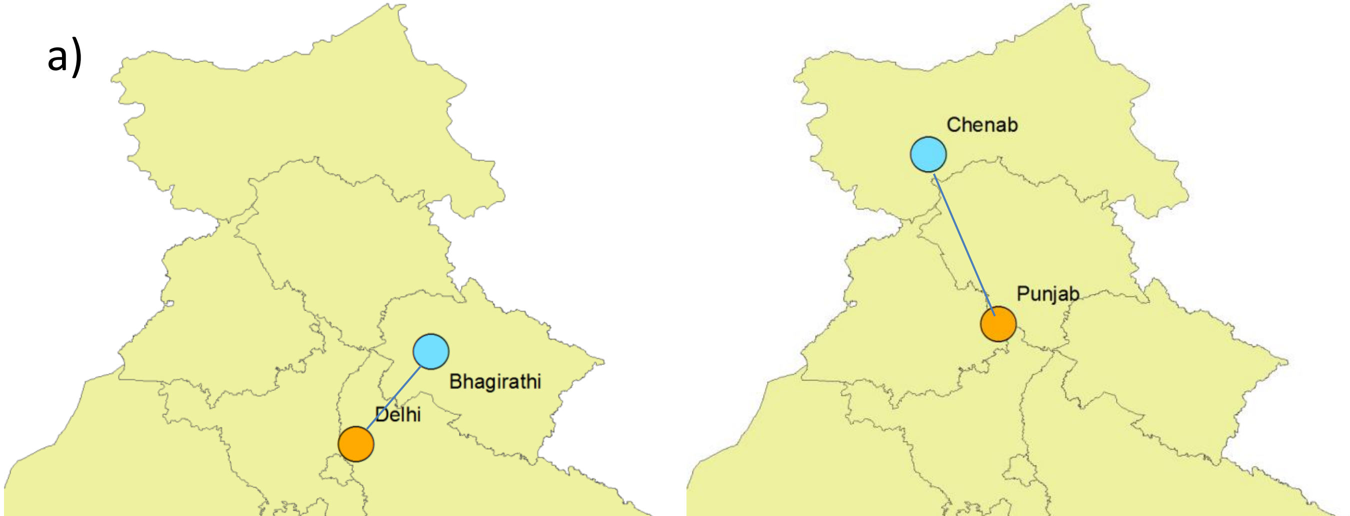
-Solar energy contribution is quite constant throughout the year with some fluctuations in the Monsoon. Hydro and diesel work as complementary to each other.



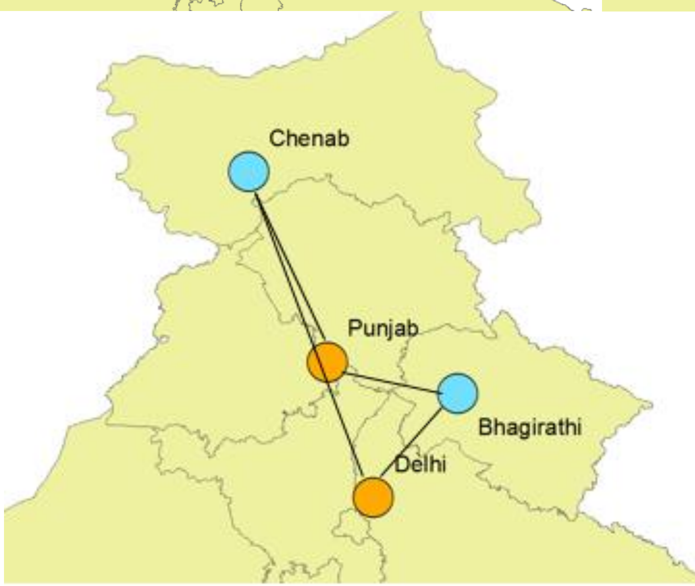
Isolated vs. Connected Systems

What is the required hydropower generation capacity and storage along with the minimal diesel usage to support 1 GWpeak solar power

a)



b)

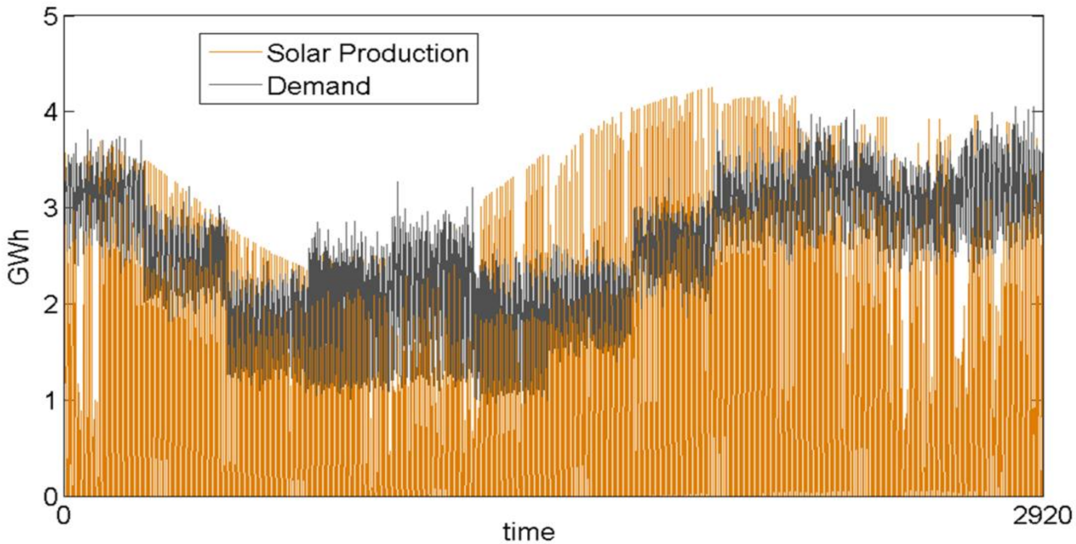


- Combined systems generates more hydropower with 40% smaller reservoir size.
- The overall cost of the objective function is decreased by 46%

Solar Power Curtailment

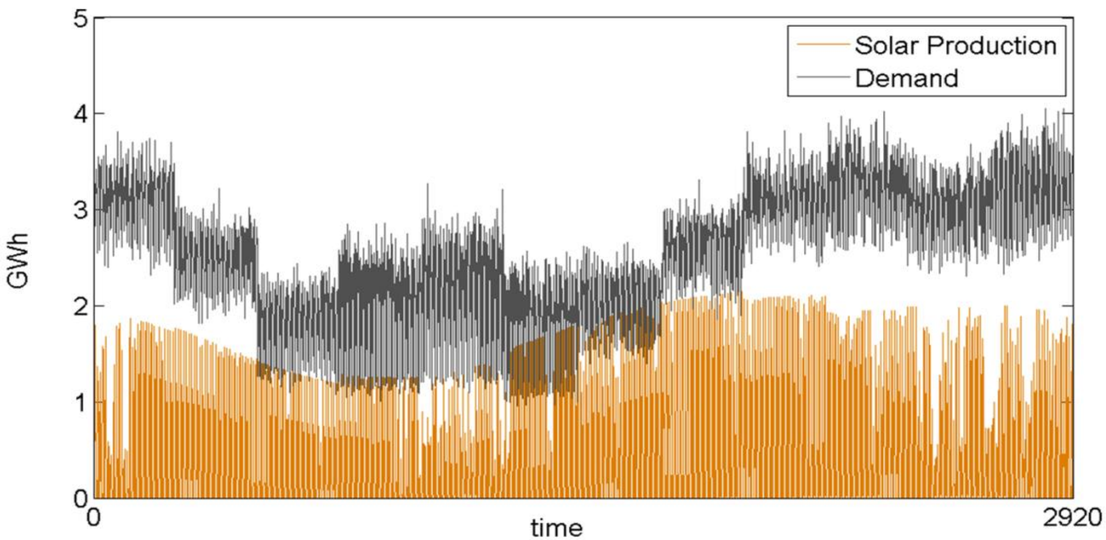
Operating solar power generators below their maximum energy generation levels may reduce the unit cost of the system.

a)



Solar efficiency: %90
Unit cost of solar:5.2 cents/kWh
Unit cost of the system: 8.7 cents/kWh

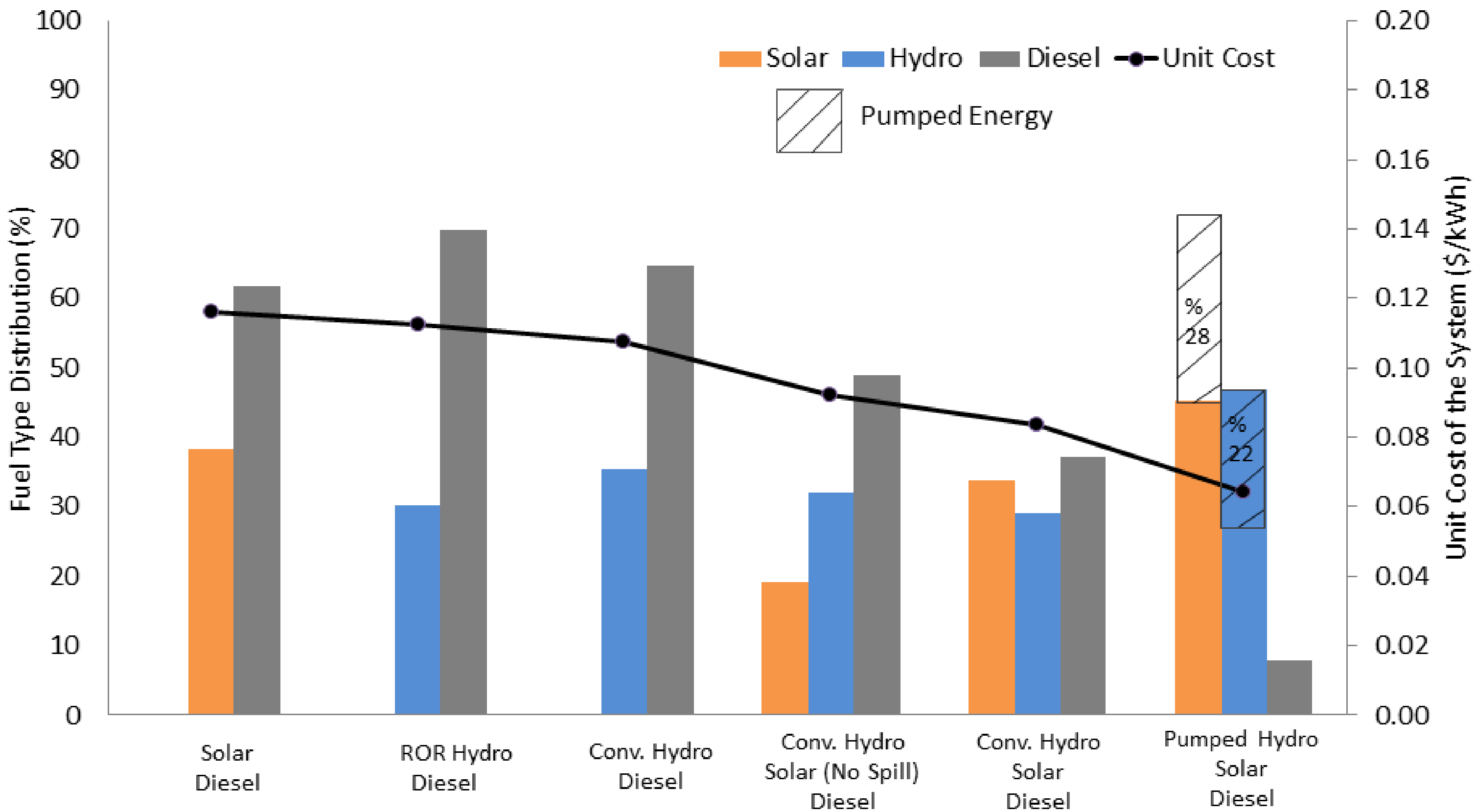
b)



Solar efficiency : 100%
Unit cost of solar:4.7 cents/kWh
Unit cost of the system:9.2 cents/kWh

Results- Pumped Hydro System

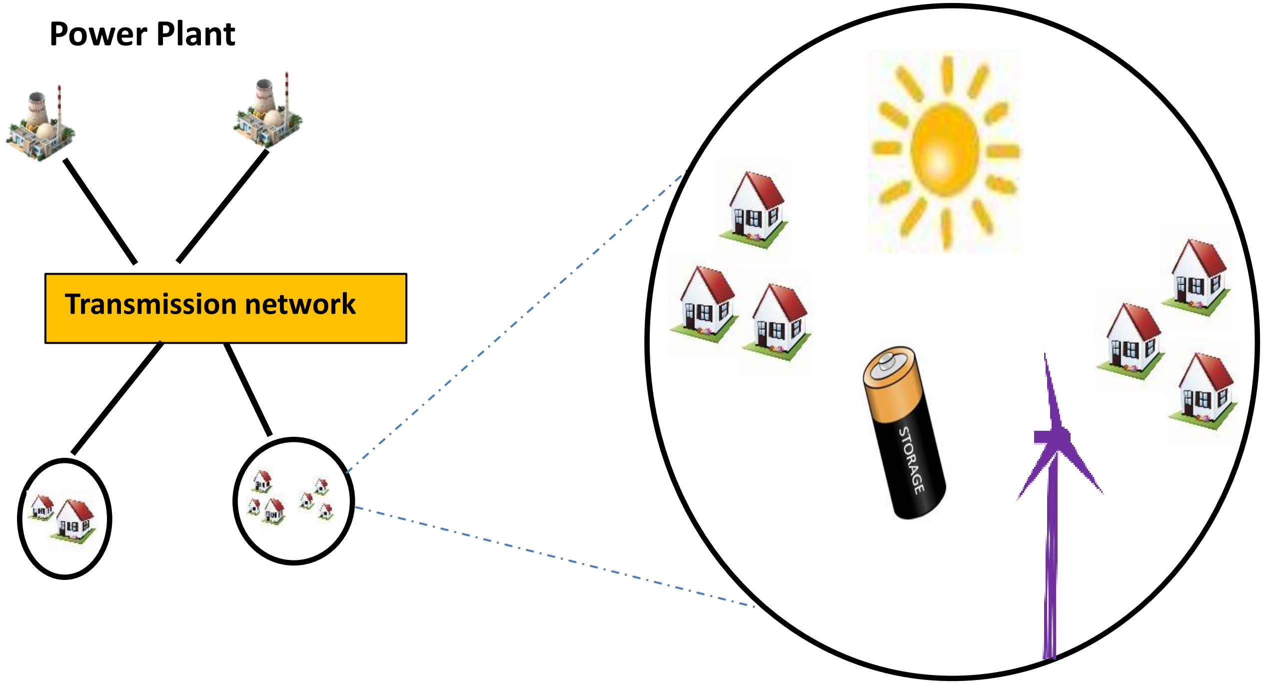
-Single basin, single demand point, single scenario case



	Solar Diesel	ROR Hydro Diesel	Conv. Hydro Diesel	Conv. Hydro Solar (No Spill) Diesel	Conv. Hydro Solar Diesel	Pumped Hydro Solar Diesel
Upper Reservoir (km3)	-	-	0.24	0.24	0.29	0.15
Lower Reservoir (km3)	-	-	-	-	-	0.04
Generator (GW)	-	1.09	1.13	1.05	1.06	1.50
SolarPanel (km2)	16.61	-	-	6.42	12.50	28.18

Multi-objective Optimization of Grid-Connected Decentralized Energy Systems

- minimize CO2
- minimize Cost



Thank you!


When there's a huge solar energy spill,
it's just called a "nice day"
www.votesolar.org