# Reliable-Affordable-Resilient Smart Grids

## from United States to Uganda to United Nations


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Industry Collaborators: Mulago Hospital, Virika Hospital, Bosch International, Homer Energy



Previous Funding: ND Energy, UM-Michigan Memorial Phoenix Energy Institute, UM-Office of Vice President and Research, UM-African Studies Center, UM-William Davidson Institute, NSF-RCN, Bosch International


ESDD - RESEARCH LAB

ENERGY AND SUSTAINABLE DEVELOPMENT WITH DESIGN

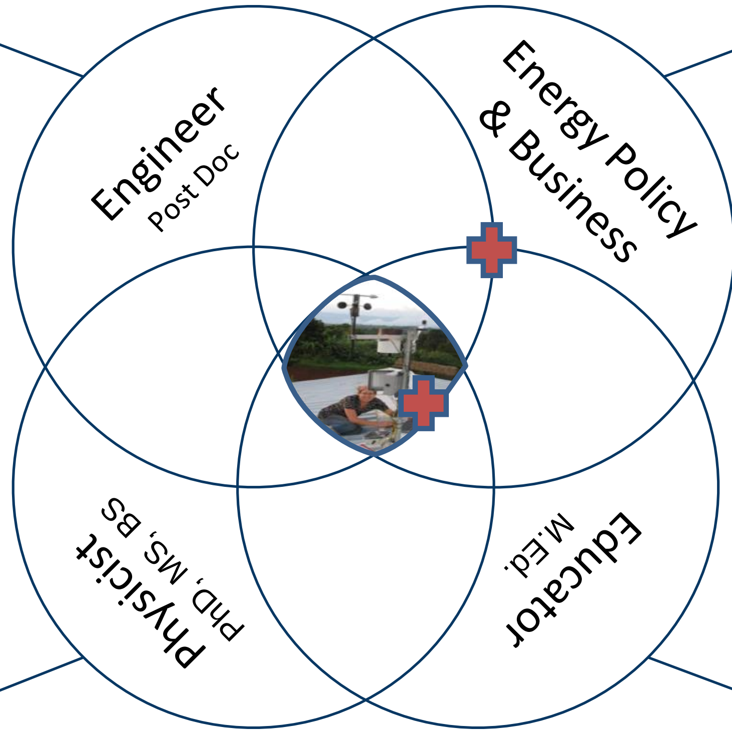
* Today's speaker

# Abigail Mechtenberg

Energy and Sustainable Development Researcher, Center of Sustainable Energy, University of Notre Dame
Assistant Teaching Professor, Physics Department, University of Notre Dame


## Academic Publications

Energy and Sustainable Development




## Academic Publications

Design and Control
Optimization with
Novel Objective for
Power Management

## Empower Energy Design

International Organization
to Change
Design Paradigm
Toward Innovation

## Energy Curriculum

for Physics, Engineering, Sustainability, and Business Curricula

ESDD - RESEARCH LAB

ENERGY AND SUSTAINABLE DEVELOPMENT WITH DESIGN

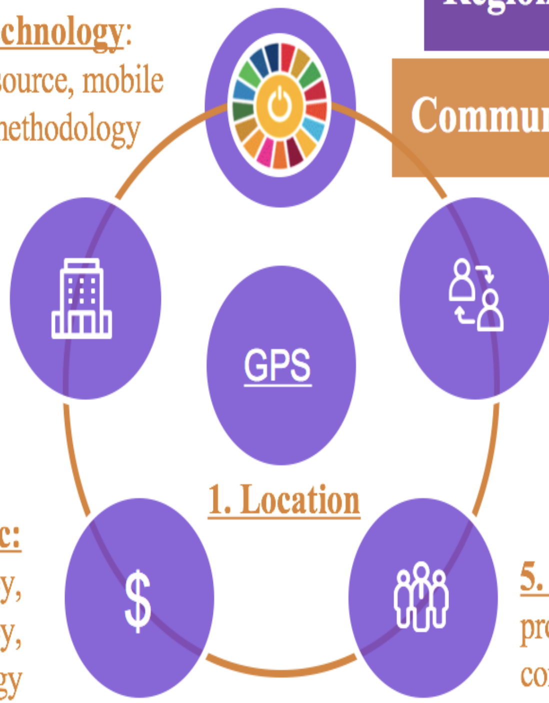
# Data Collection & Management

**Global Standards:** Comparability, Sensors, Crowdsourcing/ Swarm, Citation/Outside Links from Data Management Location

**National Standards:** Frameworks, Capacity Transformation

**Regional Standards:** Networks, Interconnected

**Community Standards:** Interdependent, Energy Ethics




**1. Location**

**2. Energy Technology**: sensors, open source, mobile phones, GIS, methodology

**3. Social:** survey tool, demand type (HH, health, education, business, etc.), methodology

**4. Economic:** data collection costs money, data collection generates money, methodology

**5. Peer Reviewed and/or Crowd Sourcing:** process, validation, recollection, verification, conflict of interest forms, maps, methodology

**6. Transmission/Management:** upload/download - emailed, texted, mobile app, internet, security

**Foundation:** National Energy Database by Ministry of Energy and United Nations SEforALL – Creative Commons, Uploaded Organization Identification, Energy Ethics Documentation Data Agreement

THE SUSTAINABLE ENERGY FOR ALL CHARRETTES
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# Smart Grids
# Reliable, Affordable, and Resilient

1. **Energy Crisis**
   **<u>in Health Care</u>**
   **LMIC facilities**
   **research results**

2. **Energy $E^3$**
   **<u>Innovation</u>**
   **Energy Education, Engineering Design, & Entrepreneurship**

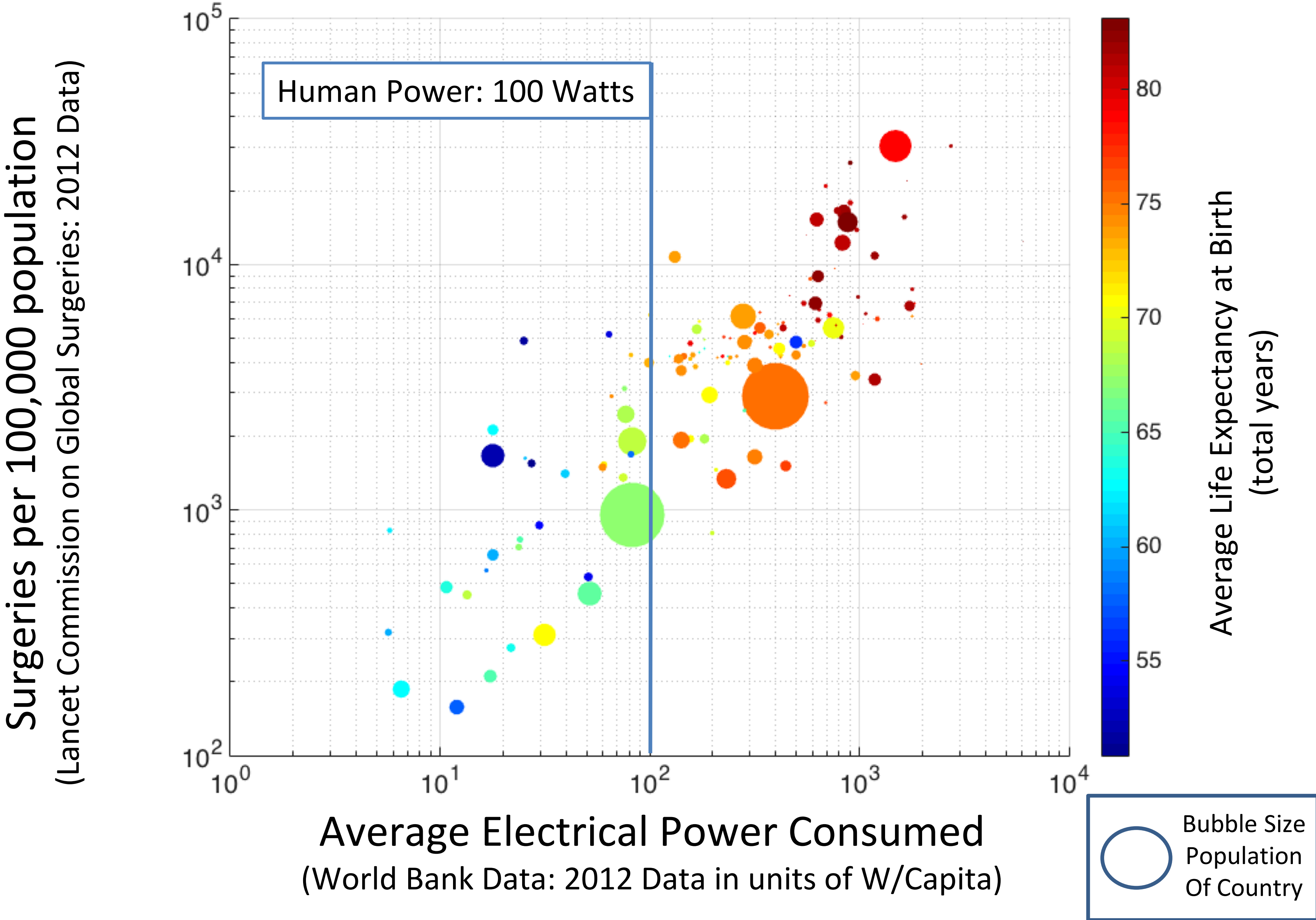
3. ~~**Energy Crisis**~~
   ~~**<u>in Military</u>**~~
   ~~**FOBs V2G2G**~~

4. ~~**Energy Crisis**~~
   ~~**<u>in Transportation</u>**~~
   ~~**Diversifying Transportation**~~

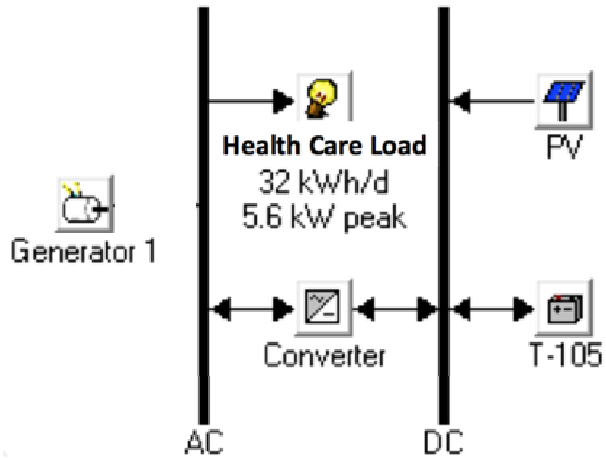
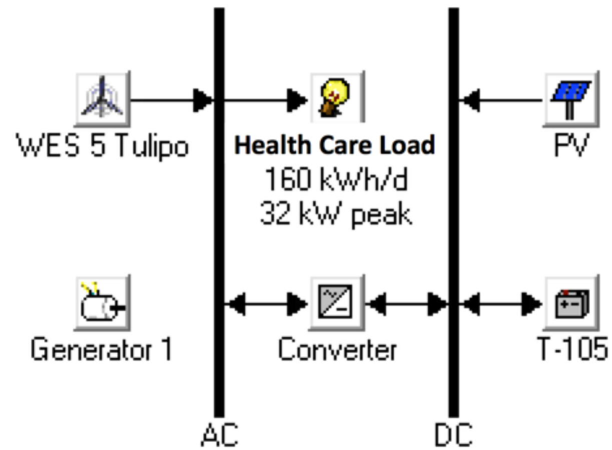
5. **<u>Assumptions in Smart Grid</u>**
   **HIC and LMIC MIT A+B results**

**Image Credit:**
United Nations Development Program - Sustainable Energy for All Forum Logo, 2018
https://www.seforall.org/content/first-round-speakers-announced-2017-seforall-forum

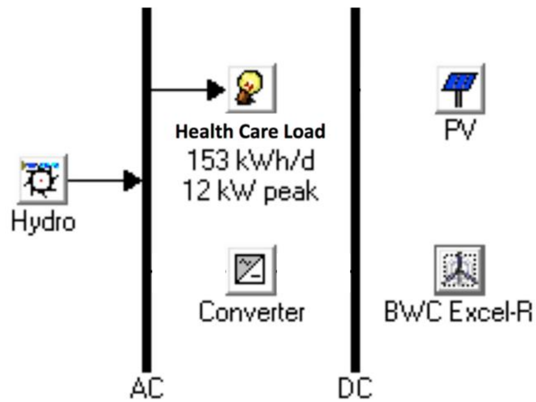
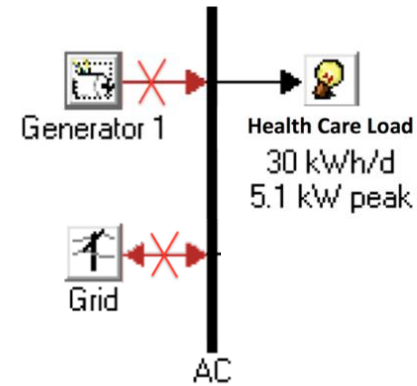
# Global Surgeries vs Average Electrical Power Consumed



# Modeling Electricity and Health Care
# Part A (sites 1 & 2)

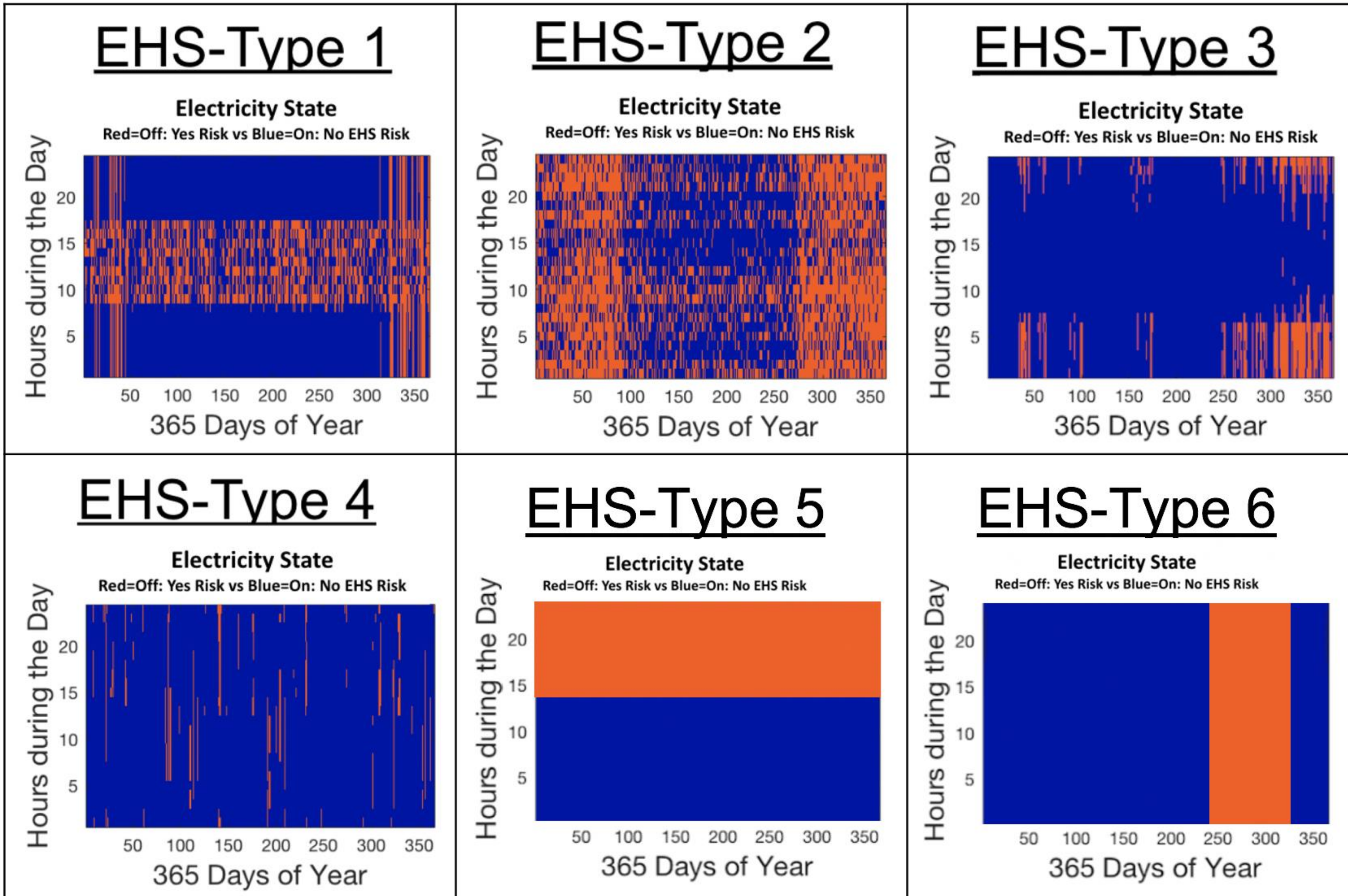
| | Iraq - *Solar Energy,* 2010<br> | Bangladesh - *Energy*, 2010<br> |
|---|---|---|
| Cost of Electricity ($/kWh) | $0.26/kWh | $0.51/kWh |
| Energy Capacity Shortage (%) $\frac{E_{not\ served}}{E_{total}}$ | 18 % | 10 % |
| Time Capacity Shortage (%) $\frac{t_{not\ served}}{t_{total}}$ | 25 % | 6.6 % |
| Failures (hrs/year) | 2160 hours | 574 hours |
| Back-up System | Install Solar<br>no backup chosen | Install Solar+Wind<br>no backup chosen |

# Modeling Electricity and Health Care Part B (sites 3 & 4)

| | Ghana - *International Journal of Computer Applications*, 2015<br><br> | Uganda - *ISSST-IEEE*, 2012<br><br> |
|---|---|---|
| Cost of Electricity ($/kWh) | $0.12/kWh | Grid: $0.25/kWh - Diesel: $0.75-11/kWh |
| Energy Capacity Shortage (%) $\frac{E_{not\ served}}{E_{total}}$ | 11 % | 4.1 % |
| Time Capacity Shortage (%) $\frac{t_{not\ served}}{t_{total}}$ | 49 % | 4.0 % |
| Failures (hrs/year) | 4289 hours | 355 hours |
| Back-up System | Government Grid: Hydro base power, Facilities: Provide their own peak power | Year of Data on Voltage and Current Grid+Diesel Generator |

# Energy Healthcare System Example

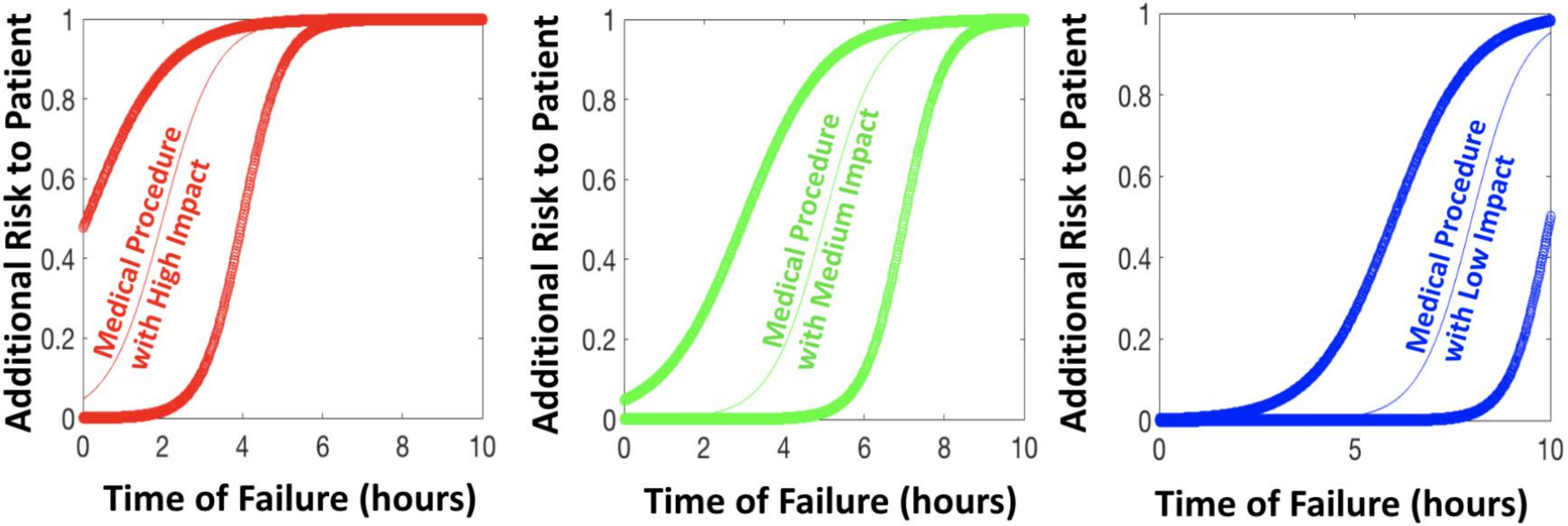
## Part A – Electricity Failure Pattern



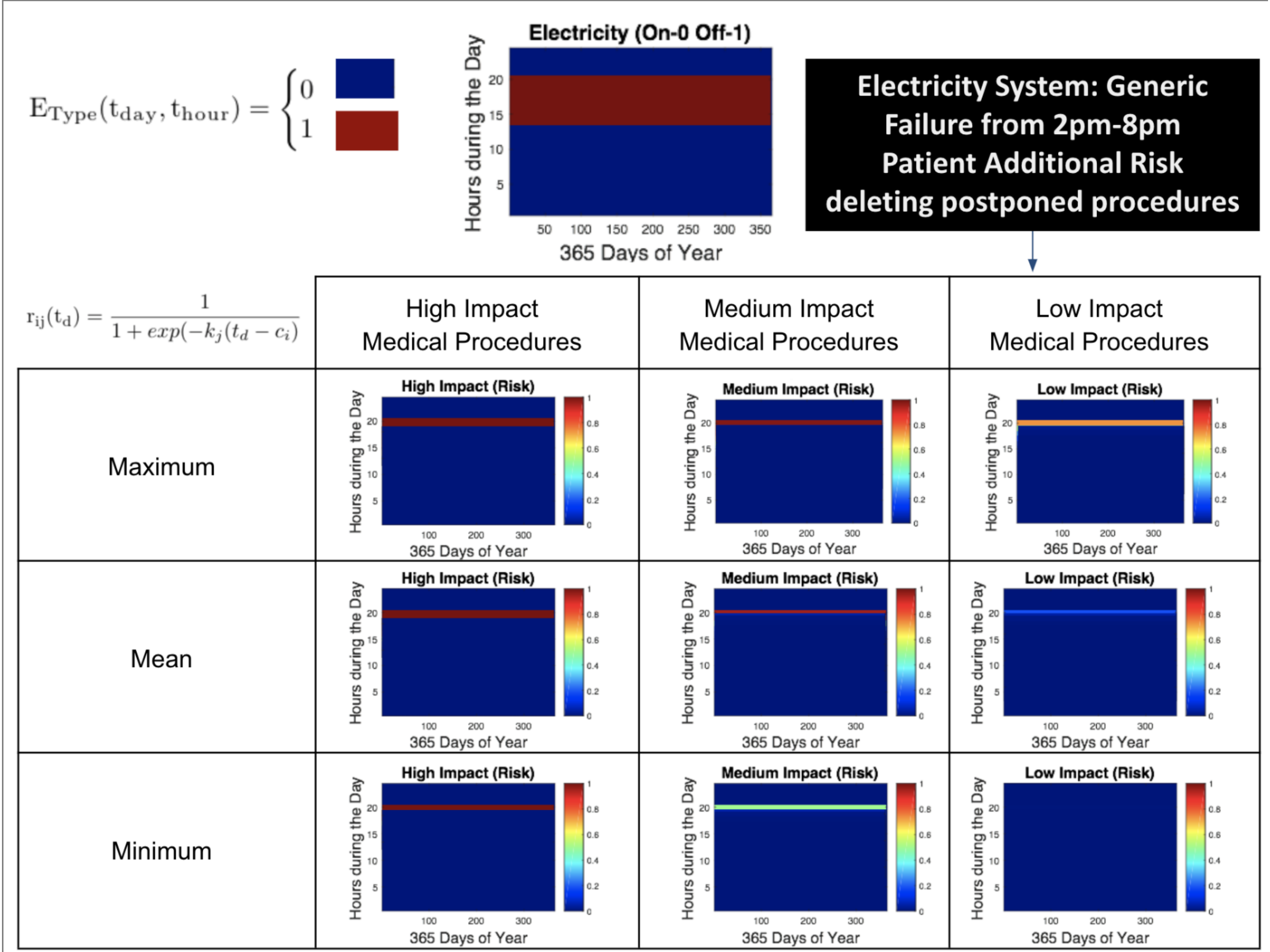
# Energy Healthcare System Example
## Part B - Additional Risk to Patient

$$r_{ij}(t_d) = \frac{1}{1 + exp(-k_j(t_d - c_i))}$$

$$\begin{cases} i: 1 \text{ to } 3 \text{ for low, medium, and high impact medical procedure} \\ j: 1 \text{ to } 3 \text{ for minimum, mean, and maximum for uncertainty in risk} \\ c_i: \text{ time at which risk is 50\%} \\ k_j: \text{ slope of the risk function for the time in which risk is 50\%} \\ t_d: \text{ duration of electricity failure (in hours)} \end{cases}$$

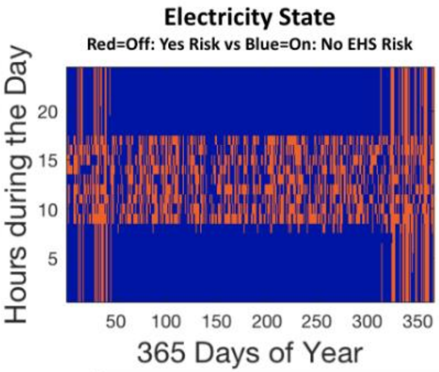



- Medical Procedures can be placed into four impact categories: high, medium, low, no
- Horizontal Axis: duration of electricity failure (mean bounded by uncertainty)
- Vertical Axis: additional risk to patient increases as duration of failure increases

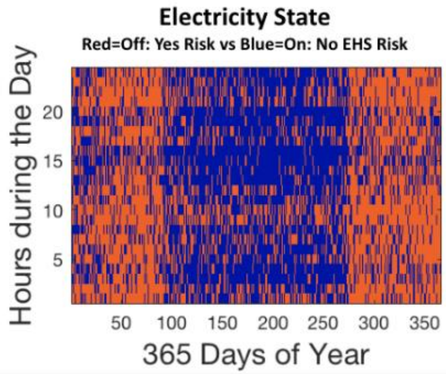

$E_{Type}(t_{day}, t_{hour}) = \begin{cases} 0 \\ 1 \end{cases}$
Electricity (On-0 Off-1)
Hours during the Day
365 Days of Year
Electricity System: Generic Failure from 2pm-8pm Patient Additional Risk deleting postponed procedures
$r_{ij}(t_d) = \frac{1}{1 + exp(-k_j(t_d - c_i)}$
High Impact Medical Procedures
Medium Impact Medical Procedures
Low Impact Medical Procedures
Maximum
Mean
Minimum
High Impact (Risk)
Medium Impact (Risk)
Low Impact (Risk)

# Energy Healthcare Systems (EHS) Comparisons

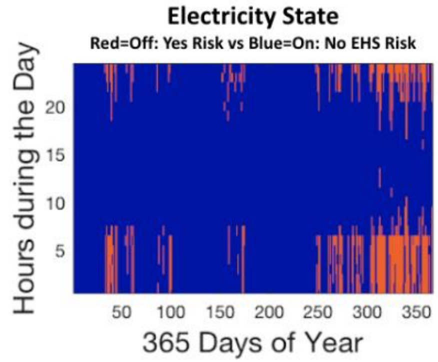
## EHS-Type 1



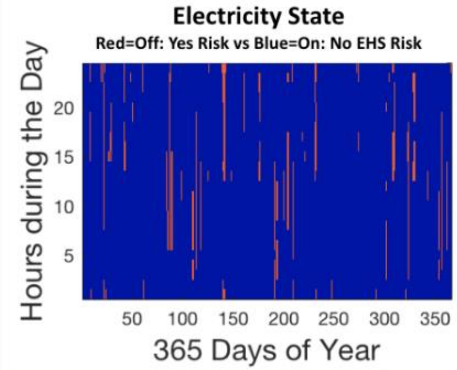

## EHS-Type 2




## EHS-Type 3



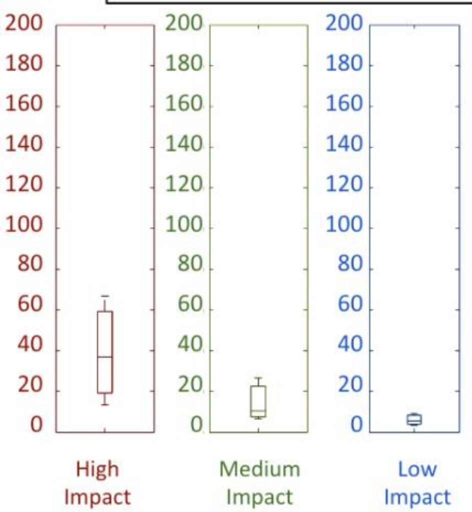

## EHS-Type 4

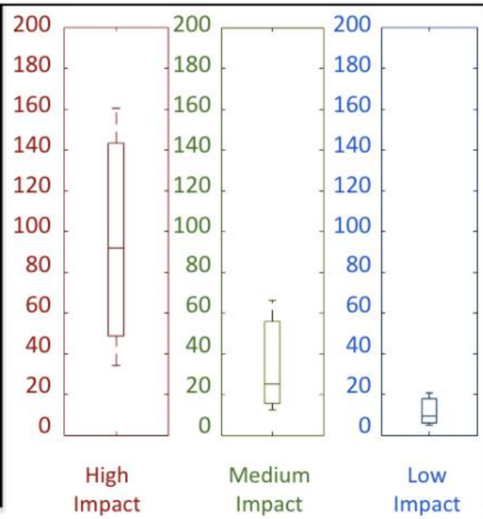


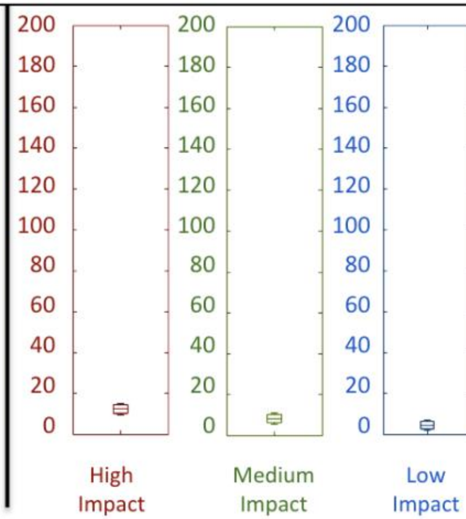

Above Electricity Failure events result in

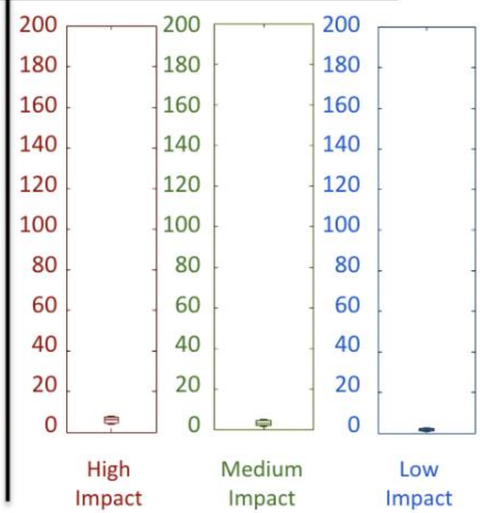
**Additional Risk to Patients (in units of Deaths per 1,000 Patients)**

for Medical Procedures in 3 Categories: High, Medium, & Low Impact




Deaths per 1,000 over the entire year, but only considers the final additional risk (deleted all risks from postponing medical procedure).

# Jinja Regional Referral Hospital

## Total: 500 hospital beds → 60,833 patients/year

EHS-Type 4: Random Failures during the Year - Total Failures 4%

45% High Impact, 20% Medium Impact, 20% Low Impact, 15% No Impact

| 500 beds - Size | Deaths Min | Deaths Mean | Deaths Max |
|---|---|---|---|
| Medical Procedures with High Impact: 45% | 107 | 169 | 217 |
| Medical Procedures with Medium Impact: 20% | 20 | 37 | 61 |
| Medical Procedures with Low Impact: 20% | 11 | 18 | 29 |
| Medical Procedures with No Impact: 15% | 0 | 0 | 0 |

## Jinja Modeled Deaths

Total Yearly Deaths = 224 within uncertainty of [138, 307]

# ESH - Risk Chart – for LMIC Regional Hospital & EHS-Type 1

**Health Care Facility System (Size=150 beds High=5% Med=10% Low=20% No Impacts=65%) and Energy System (EHS-Type 1 Electricity Failure Rate)**
**(units in Number of Days in a Year that Risk will be Experienced)**

| Severity | Improbable | Remote | Occasional | Probable | Frequent |
|---|---|---|---|---|---|
| **Catastrophic** High Chance of 2 Deaths during Day | | | 27 Days | 14 Days | 9 Days |
| **Significant** Low Chance of 2 Deaths during Day | | | 24 Days | 2 Days | |
| **Moderate** High Chance of 1 Death during Day | | | 19 Days | 1 Days | 1 Days |
| **Minor** Low Chance of 1 Death during Day | | | | | |
| **Negligible** Extremely Low Chance of 1 Death During Day | 47 Days | 121 Days | 65 Days | 11 Days | 9 Days |
| **Likelihood** | 0-2 hrs Time in a Failure Event during Day | 2-5 hrs Time in a Failure Event during Day | 5-10 hrs Time in a Failure Event during Day | 10-15 hrs Time in a Failure Event during Day | 15-24 hrs Time in a Failure Event during Day |

- Below + considering On-demand Energy Systems
- Below + Postpone Procedures
- Below + Check Energy Stored before Starting Procedure
- No Change to Procedure*
- No Change to Procedure: Traditional Backup

* Strongly consider adding another backup system for hybridization and diversification of energy systems before risks increase.

# ESH - Risk Chart – for LMIC Regional Hospital & EHS-Type 1

**Health Care Facility System (Size=150 beds High=5% Med=10% Low=20% No Impacts=65%) and Energy System (EHS-Type 1 Electricity Failure Rate)**
**(units in VSL/E - $/kWh and in Number of Days in a Year that Risk will be Experienced)**

| Severity | Improbable<br>0-2 hrs Time in a Failure Event during Day | Remote<br>2-5 hrs Time in a Failure Event during Day | Occasional<br>5-10 hrs Time in a Failure Event during Day | Probable<br>10-15 hrs Time in a Failure Event during Day | Frequent<br>15-24 hrs Time in a Failure Event during Day |
|---|---|---|---|---|---|
| **Catastrophic**<br>High Chance of 2 Deaths during Day | | | 27 Days<br>$24,243/kWh | 14 Days<br>$14,996/kWh | 9 Days<br>$9,378/kWh |
| **Significant**<br>Low Chance of 2 Deaths during Day | | | 24 Days<br>$12,323/kWh | 2 Days<br>$957/kWh | |
| **Moderate**<br>High Chance of 1 Death during Day | | | 19 Days<br>$6,728/kWh | 1 Day<br>$412/kWh | 1 Day<br>$412/kWh |
| **Minor**<br>Low Chance of 1 Death during Day | | | 14 Days<br>$4,061/kWh | | |
| **Negligible**<br>Extremely Low Chance of 1 Death During Day | 47 Days<br>$739/kWh | 121 Days<br>$12,057/kWh | 65 Days<br>$13,421/kWh | 11 Days<br>$846/kWh | 9 Days<br>$0/kWh |

**Likelihood**

- Below + considering On-demand Energy Systems
- Below + Postpone Procedures
- Below + Check Energy Stored before Starting Procedure
- No Change to Procedure*
- No Change to Procedure: Traditional Backup

* Strongly consider adding another backup system for hybridization and diversification of energy systems before risks increase.

# Smart Grids
# Reliable, Affordable, and Resilient

**1. Energy Crisis**
**<u>in Health Care</u>**
**LMIC facilities**
**research results**

**2. Energy E$^3$**
**<u>Innovation</u>**
**Energy Education, Engineering Design, & Entrepreneurship**

~~**3. Energy Crisis**~~
~~**<u>in Military</u>**~~
~~**FOBs V2G2G**~~

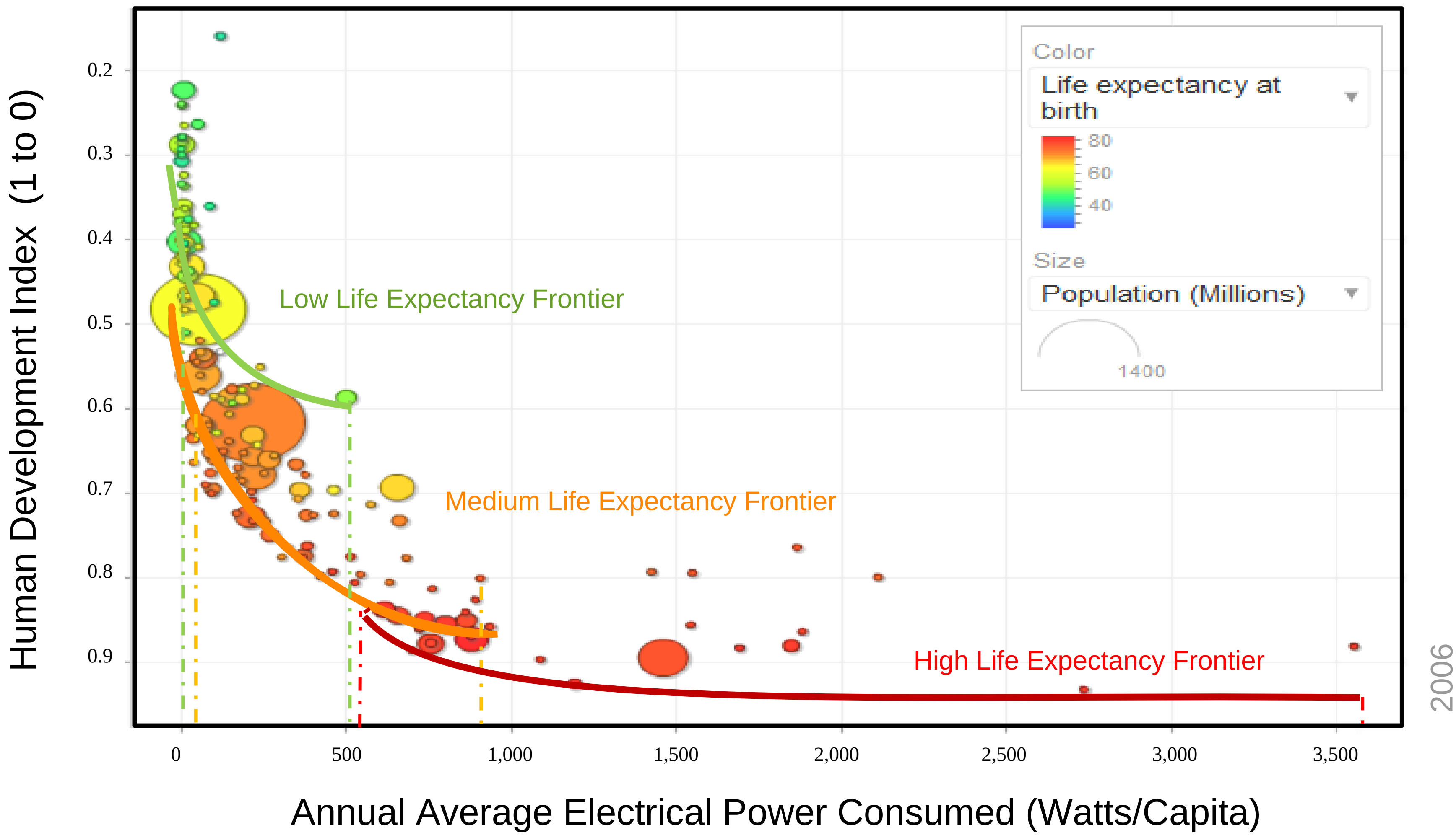
~~**4. Energy Crisis**~~
~~**<u>in Transportation</u>**~~
~~**Diversifying Transportation**~~

**5. <u>Assumptions in Smart Grid</u>**
**HIC and LMIC MIT A+B results**

**Image Credit:**
United Nations Development Program - Sustainable Energy for All Forum Logo, 2018
https://www.seforall.org/content/first-round-speakers-announced-2017-seforall-forum

# Countries Grouped into Three Electricity and HDI Frontiers

(EIA, UNDP, UN-Population Data)



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Phone: +1(734) 719 0432 | e-mail: empowerdesignenergy@gmail.com

# Energy E³ Innovation

Changing Design Paradigm

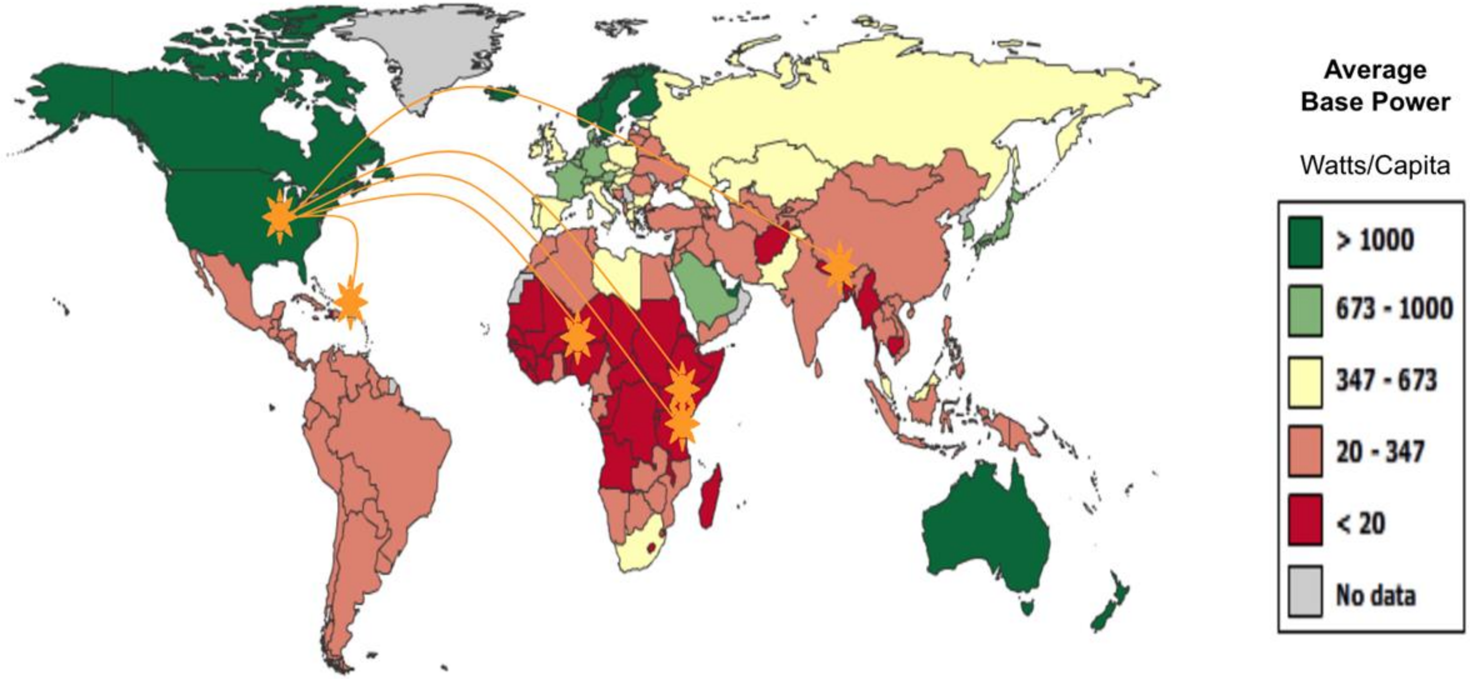
STOP **Design FOR the other 90%**[1]

**Design WITH the other 90%**[2]

GO **Design BY All**[3]


1. Smith, Cynthia E. *Design for the Other 90%*. New York: Smithsonian, Cooper-Hewitt, National Design Museum, 2007. Print.
2. Smith, Cynthia E. *Design with the Other 90%: Cities*. New York: Cooper-Hewitt National Design Museum, 2011. Print.
3. Musaazi, Moses Kizza, Abigail R. Mechtenberg, Juliet Nakibuule, Rachel Sensenig, Emmanuel Miyingo, John Vianney Makanda, Ali Hakimian, and Matthew J. Eckelman. "Quantification of Social Equity in Life Cycle Assessment for Increased Sustainable Production of Sanitary Products in Uganda." *Journal of Cleaner Production* (2013).

# Global Context + Energy $E^3$ Pathway

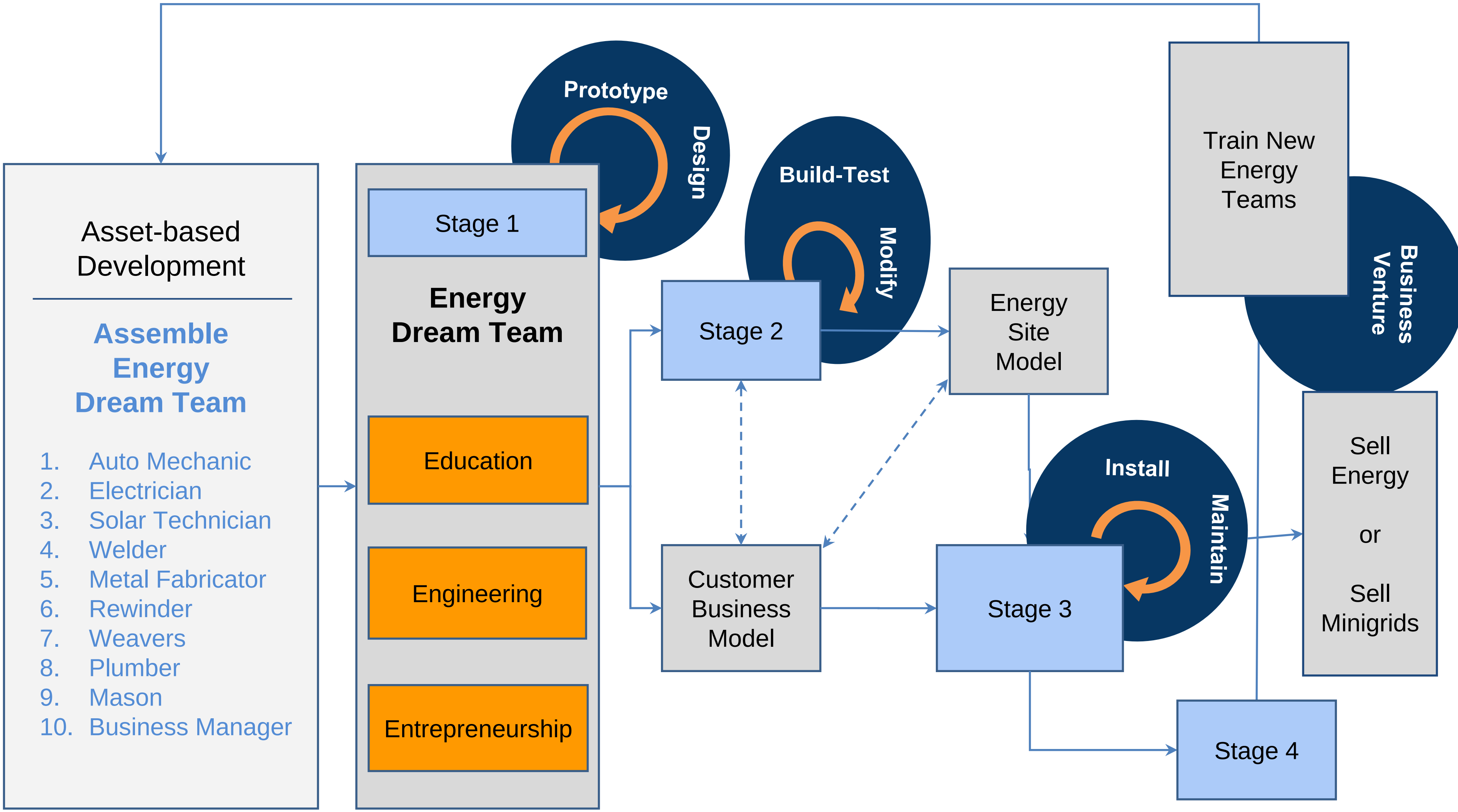



**Energy $E^3$ Pathway =**
**Energy Education + Engineering Design + Entrepreneurship**

Books/ Lecture | Prototype/ Design | Design/ Build | Test/ Modify | Deployed/ Customer | Customer/ Business Venture

Image Credit:
Human Power as a Viable Electricity Gateway for Nations below 30 W / Capita. Mechtenberg, A.R, et al., Energy for Sustainable Development, 2010

# Energy E$^3$ Pathway In Action



# Energy E³ Devices

## Mechanical to Electrical

Gravity Generator
1mW-5 W

Hand-crank Generator
50-250 W

Bicycle Generator
50-250 W

Merry-go-round Generator
100-750 W

VAWT Generator
1-50 kW

HAWT Generator
1-50 kW

Hydro Generator
1-50 kW

## Thermal to Electrical & Chemical to Thermal

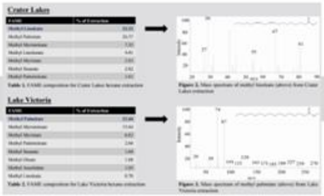
Thermal Electric Co-Gen Cookstove*
1-100 W

Waste Incinerator Generator*
1-50 kW

Concentrating Solar Power*
5-50 kW

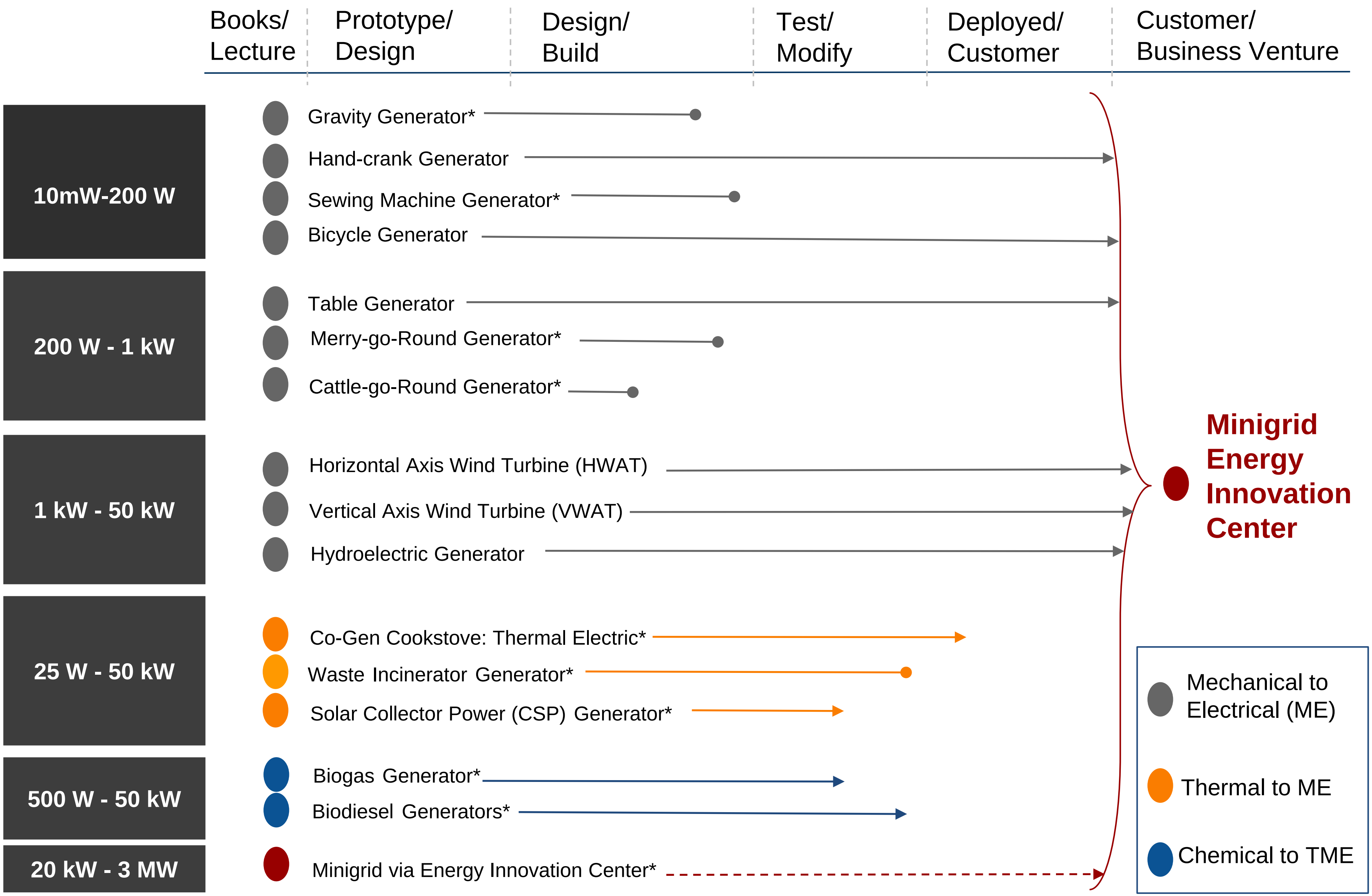
Biogas Cooking

Biogas to Petrol Generator*
5-50 kW



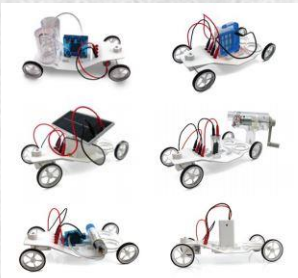
Algae into Biodiesel*
5-50 kW

# International Energy E$^3$ Team Example

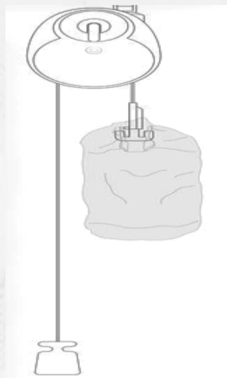


# US 6-12:

# Physics of Energy Experimental Design Labs



Kinematics
Energy Types



Gravity:
$PE_{gravity}$ to Electric

HAWT
$KE_{wind}$ to Electric

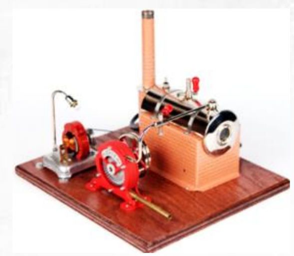
VAWT
$KE_{wind}$ to Electric

Hydroelectric
PE or KE to Electric

Solar Panels
Light to Electric

Transparent CSP
Light to TM to Electric

Thermal Electric



Power Plants
Steam Engine

Minigrid
Combining all+storage

https://sites.google.com/site/empowerenergydesignjerseycity/
Phone: +1(734) 719 0432 | e-mail: empowerdesignenergy@gmail.com

# US 6-12: Experimental Design Example

## Pulley-Mass of the pulley using two masses

**Research Question:** **How will different masses affect the mass of the pulley?**

**Hypothesis:** The masses hung from the string will not have an affect on the mass of the pulley.

**Measure:** What: Radius, Distance, Time, Mass

**Measure:** How:

- Motion Detector
- Ruler
- Scale

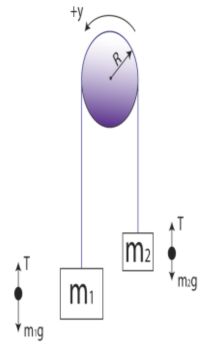
**Calculate:** What: Mass of pulley, Acceleration

**Calculate:** How: Equations

- $m=2\sum(\tau/ra)$
- $\tau= Fr\sin\theta$
- $F=ma$,
- $a=v^2/r$

**Vary:** Time to hit ground by varying the masses
(12 trials 10/20g, 20/40g, 30/50g, 50/100g, 100/200g)

**Constant:** - The pulley type
- String length




Laptop

Ruler

Motion Detector

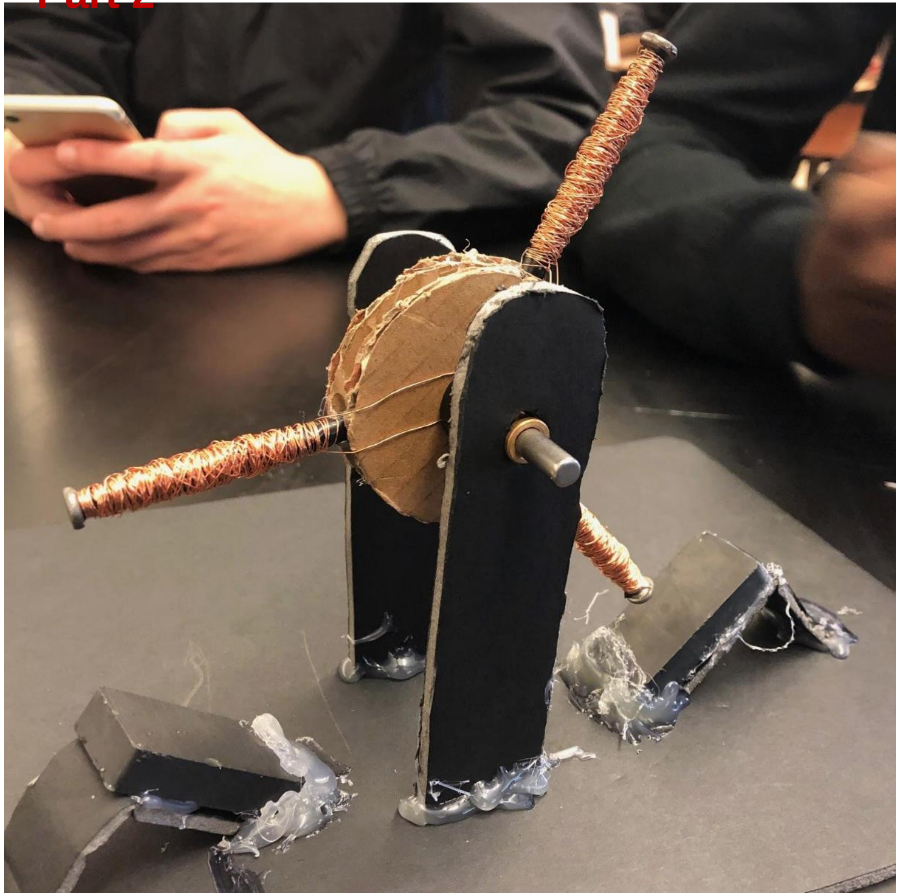
Labquest 2

**Analysis Pathway:** Graphical analysis of time versus change in mass

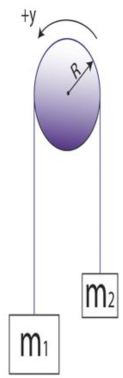
# US 6-12:
# Physics of Energy to Engineering Design

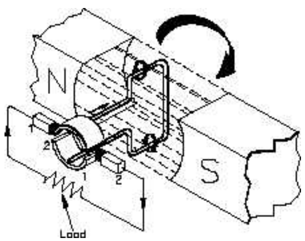
**Mechanical: Mass-Pulley of Gravity Light Part 1**

**Electrical: Generator of Gravity Light Part 2**



# US 6-12: Engineering Design to Entrepreneurship Ideation




CLOSED

**GravityLight: lighting for developing countries.**

Please click the link below to see our brand new campaign - GravityLight 2: Made in Africa

PROJECT OWNER

Patrick Hunt
London, United Kingdom
1 Campaign | More

**$399,590** USD raised by 6219 backers

CLOSED

**GravityLight 2: Made in Africa**

We believe in safe & clean light for all. Pledge now for a GravityLight & help make this a reality.

PROJECT OWNER

Caroline Angus
London, United Kingdom
1 Campaign | More

**$401,077** USD total funds raised
128% funded on July 18, 2015

INDEMAND

**nowlight: the next generation GravityLight**

Create instant light and power with the pull of a cord. 1 minute pulling generates 3 hours of light!

PROJECT OWNER

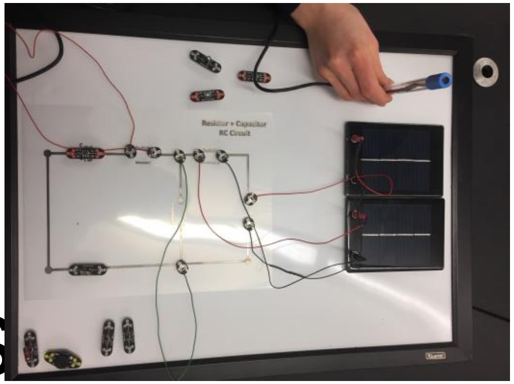
Caroline Angus
London, United Kingdom
1 Campaign | More

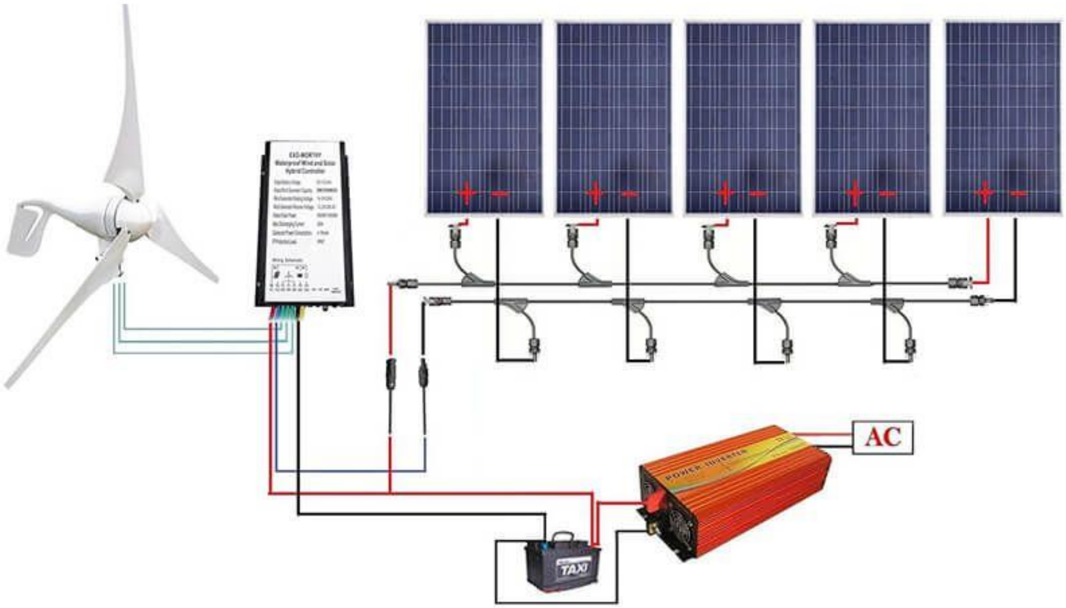
**$151,623** USD total funds raised
147% funded on July 1, 2018

Published Total: almost $1,000,000 for a device with a LCOE of $20,000/kWh

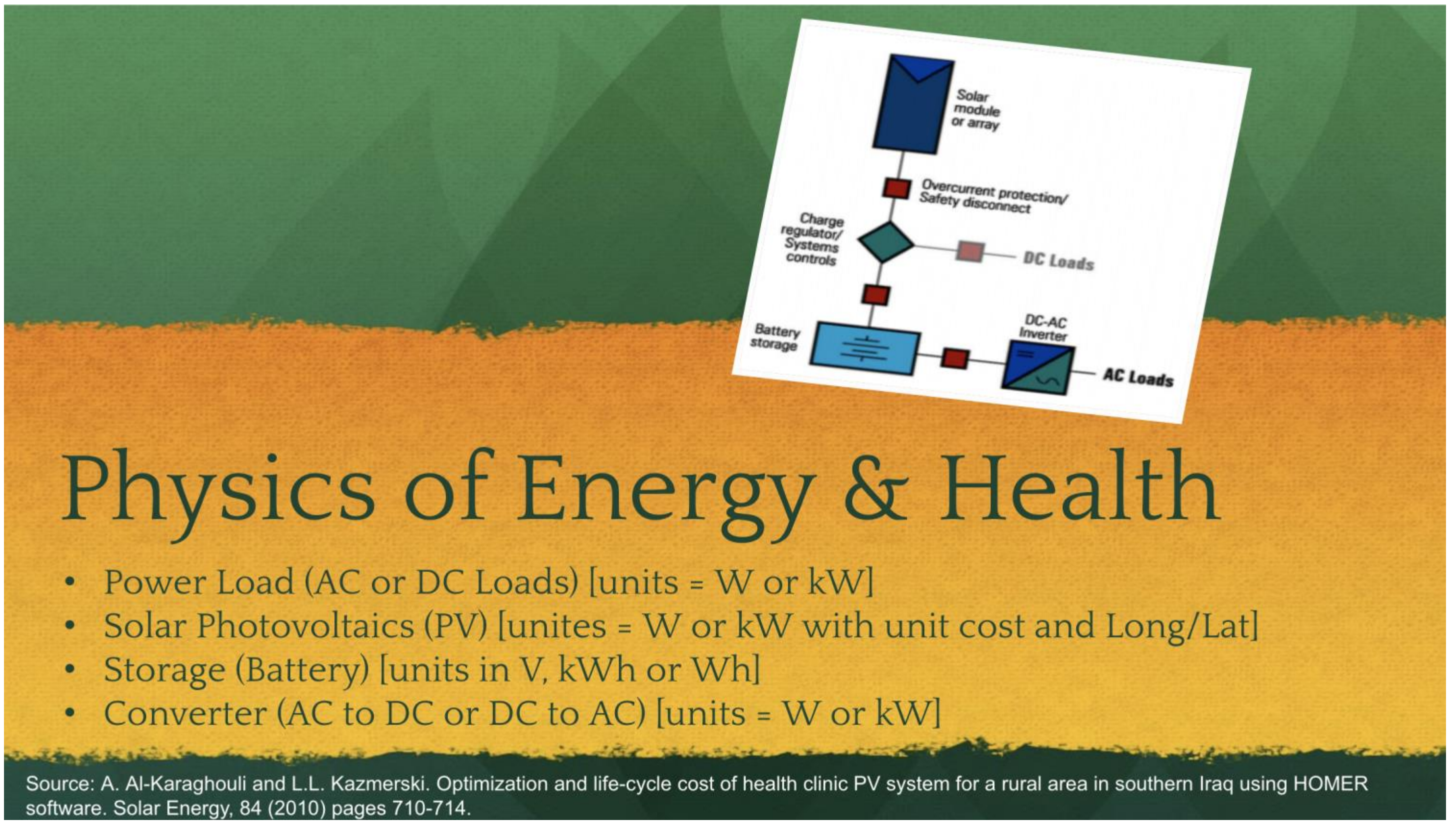
This does not include what Shell has given them

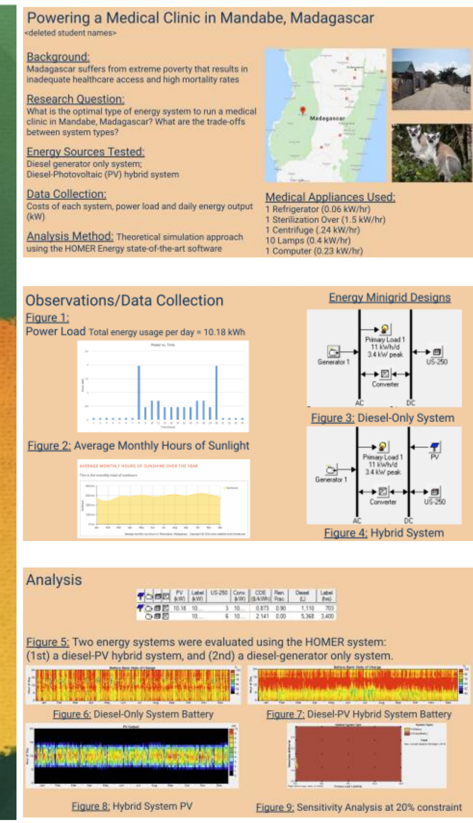
# US 6-12:
# Energy E³ Curriculum to Minigrid Expo Final Projects






# PLS I and II Labs for Pre-Meds to Designing Energy System for Health Care



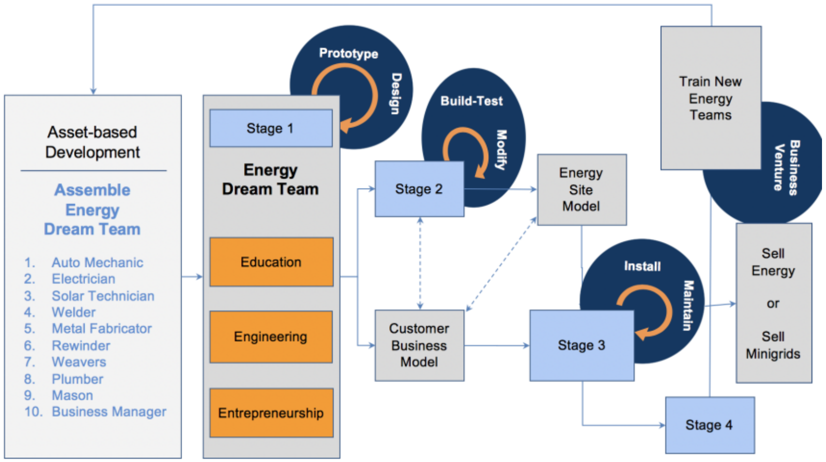




USAID
FROM THE AMERICAN PEOPLE

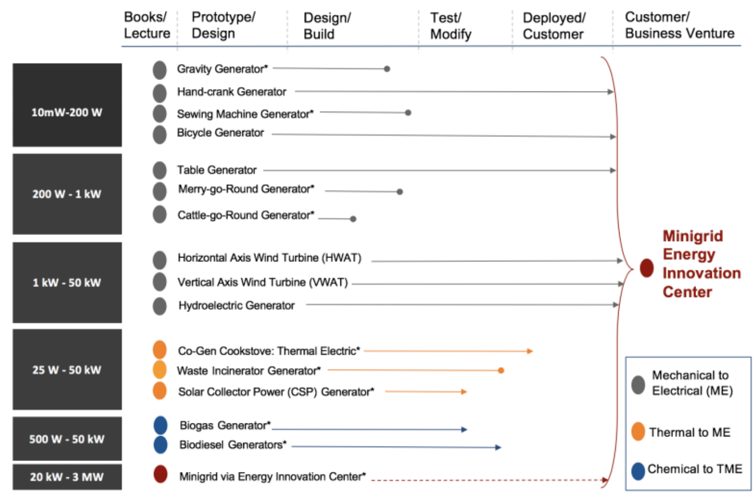
POWERING HEALTH
Electrification Options for Developing Country Health Facilities

# Action to Devices to $E^3$ Centers to Smart Grids

## Energy $E^3$ Pathway In Action




## Energy $E^3$ Pathway to Minigrid




## Energy $E^3$ Devices to Smart Grids

### Mechanical to Electrical

Gravity Generator 1mW-5 W | Hand-crank Generator 50-250 W | Bicycle Generator 50-250 W | Merry-go-round Generator 100-750 W | VAWT Generator 1-50 kW | HAWT Generator 1-50 kW | Hydro Generator 1-50 kW

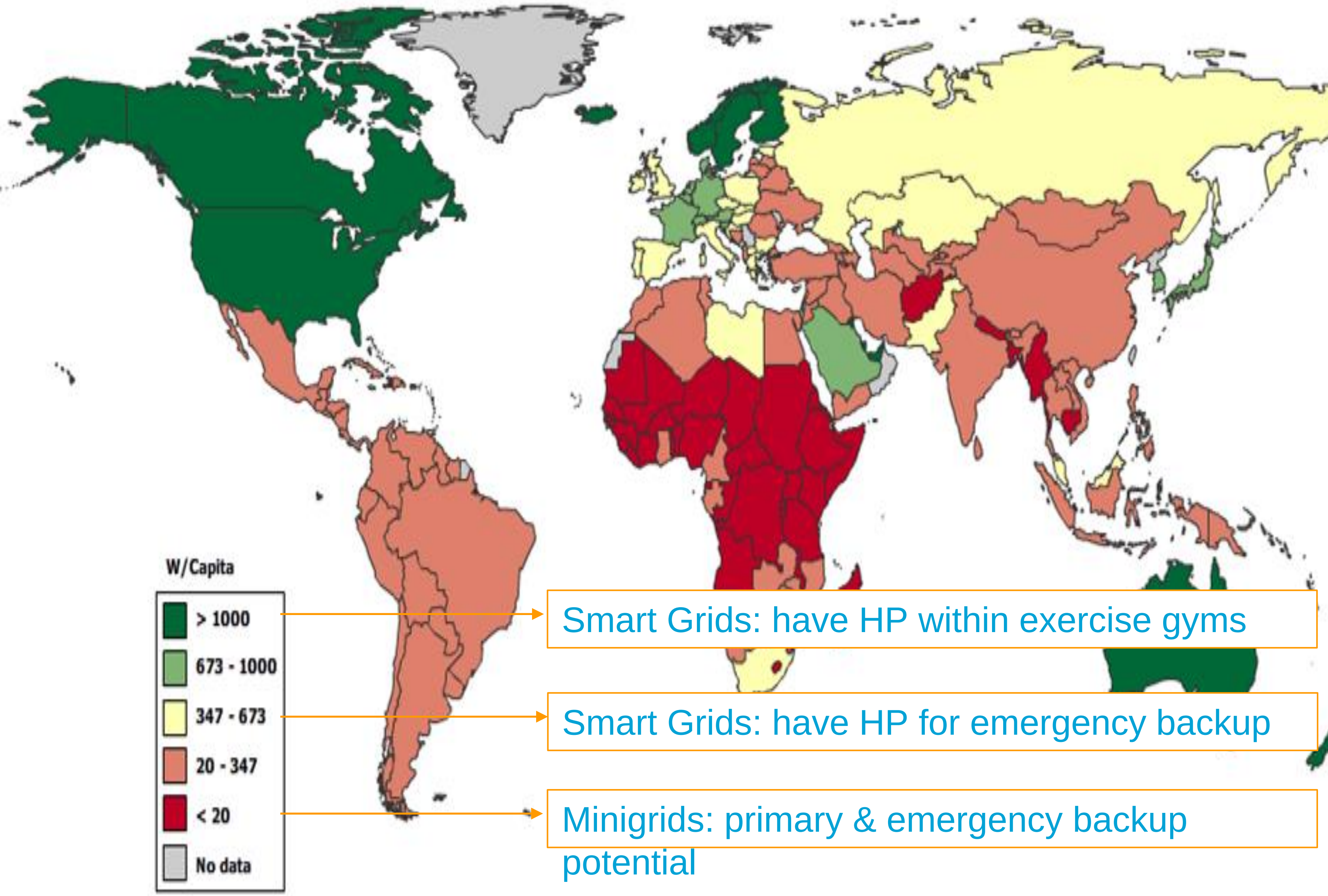
### Thermal to Electrical & Chemical to Thermal

Thermal Electric Co-Gen Cookstove* 1-100 W | Waste Incinerator Generator* 1-50 kW | Concentrating Solar Power* 5-50 kW | Biogas Cooking | Biogas to Petrol Generator* 5-50 kW | Algae into Biodiesel* 5-50 kW

## International Energy $E^3$ Innovation Center

# Electricity World Map

(EIA, UNDP, UN-Population 2008 Data)




Smart Grids: have HP within exercise gyms

Smart Grids: have HP for emergency backup

Minigrids: primary & emergency backup potential

Source: Mechtenberg, Borchers, Miyingo, Hormasji, Hariharan, Makanda, Musaazi, Human power (HP) as a viable electricity portfolio option below 20W/Capita, Energy for Sustainable Development, Volume 16, Issue 2, 2012, Pages 125-145,

# Smart Grids
# Reliable, Affordable, and Resilient

1. **Energy Crisis <u>in Health Care</u>**
   **LMIC facilities**
   **research results**

2. **Energy $E^3$ <u>Innovation</u>**
   **Energy Education, Engineering Design, & Entrepreneurship**

3. ~~**Energy Crisis in Military**~~
   ~~**FOBs V2G2G**~~

4. ~~**Energy Crisis in Transportation**~~
   ~~**Diversifying Transportation**~~

5. **<u>Assumptions in Smart Grid</u>**
   **HIC and LMIC MIT A+B results**

**Image Credit:**
United Nations Development Program - Sustainable Energy for All Forum Logo, 2018
https://www.seforall.org/content/first-round-speakers-announced-2017-seforall-forum

Applied Energy Symposium:
MIT A+B (AEAB2019)

# A Cost Effective Way to Sustain 100% Reliability using Renewable Energy (RE) Complexity

A Mechtenberg[1,2*], Henri Francois[1], Brady McLaughlin[1], Robert A Stiller[1], A Stratman[1], L Omeeboh[1]

[1]Physics Department, University of Notre Dame

[2]ND Energy, University of Notre Dame

* Corresponding senior author/speaker

icae
International Conference on Applied Energy

May 22-24, 2019 · MIT, Boston, USA
www.applied-energy.org/aeab2019

# Research Question

How can we **better** incorporate renewable energies into the grid?

Affordably → better ← Reliably

# Roadblocks

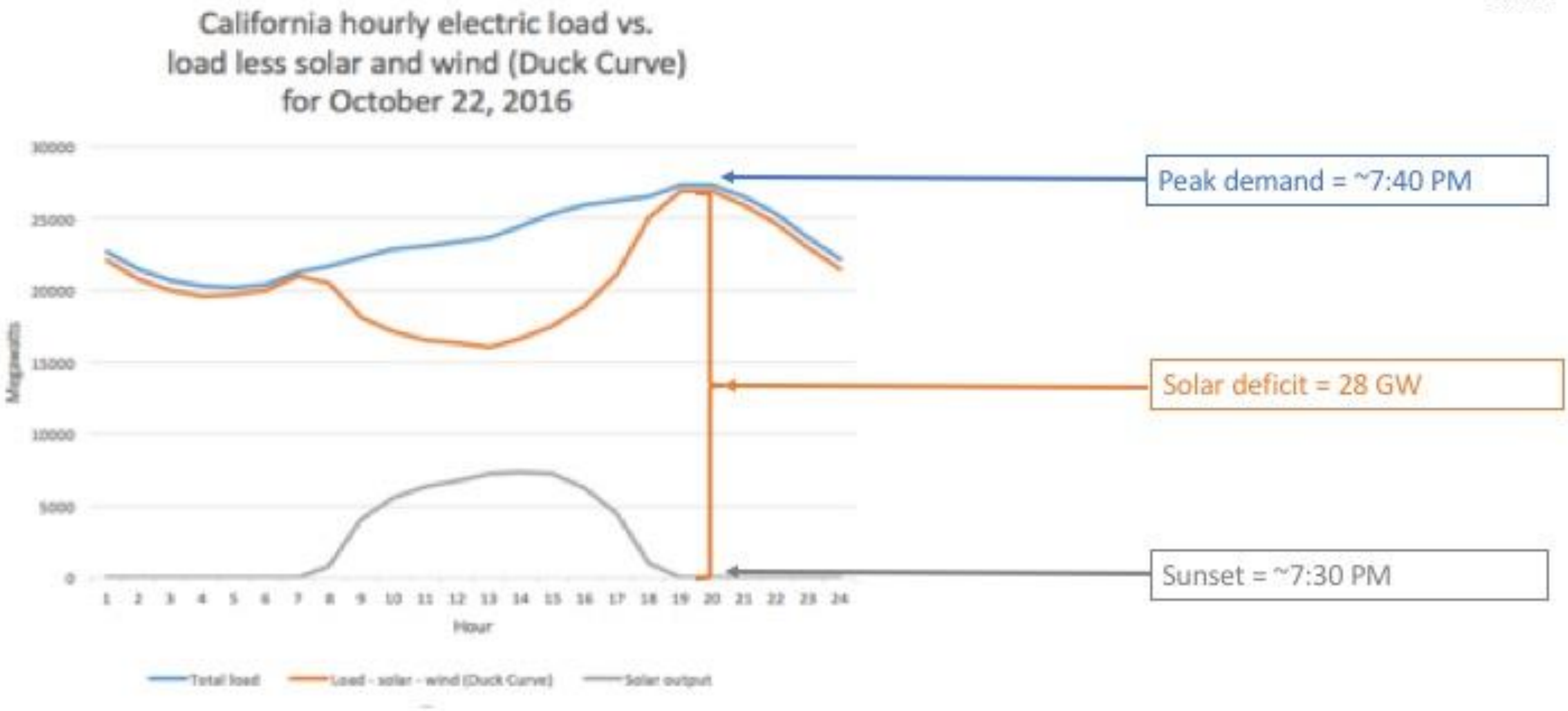
- US electricity is already cheap and reliable
- Status Quo with Solar, Wind, Batteries Adoption Slow

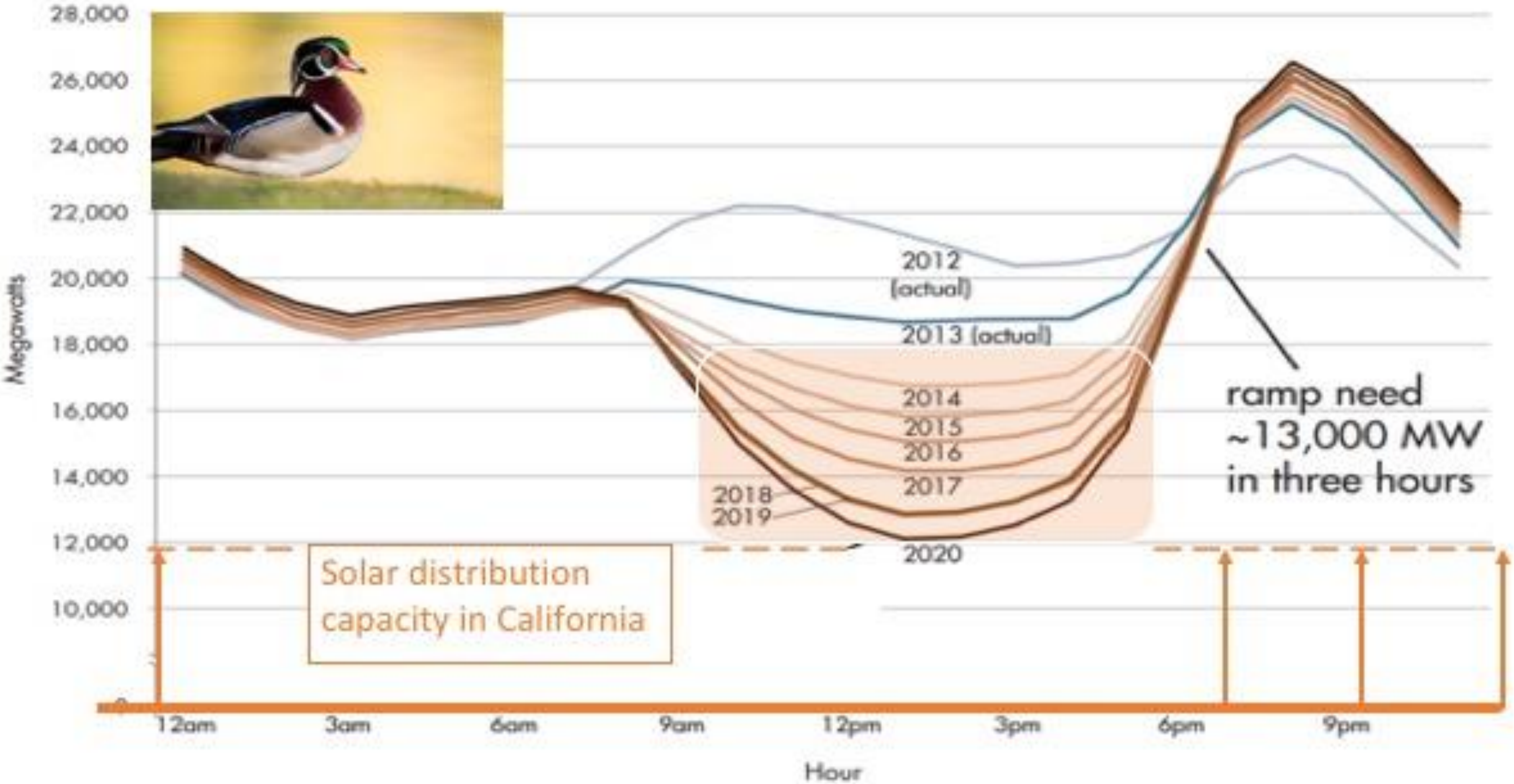
} Low incentive for change

WE MUST CHANGE ASAP

# Status Quo renewable energy incorporations are solving…

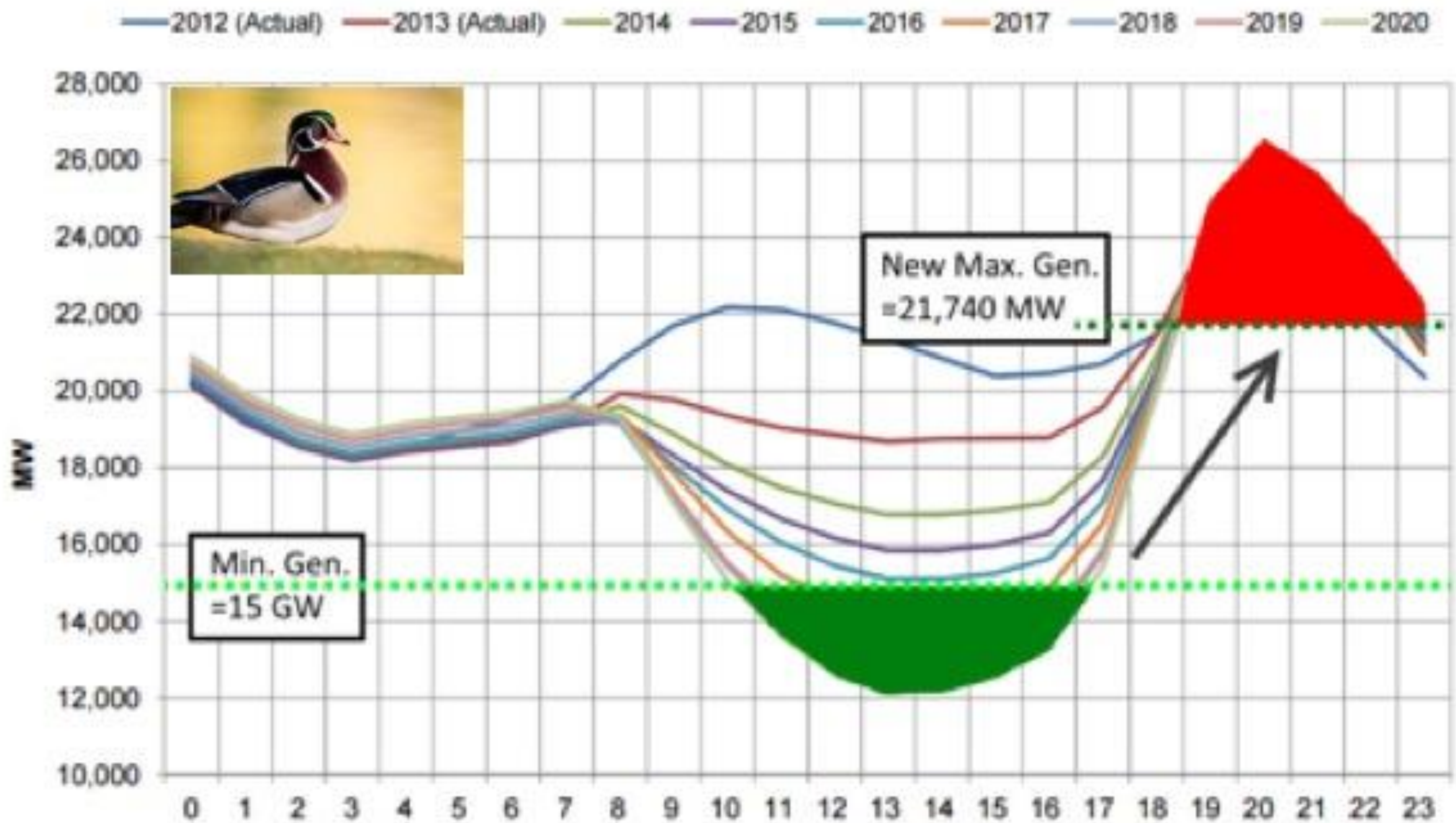
the duck curve,
for example.


California hourly electric load vs.
load less solar and wind (Duck Curve)
for October 22, 2016
30000
25000
20000
15000
10000
5000
0
Megawatts
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hour
Total load
Load - solar - wind (Duck Curve)
Solar output
Peak demand = ~7:40 PM
Solar deficit = 28 GW
Sunset = ~7:30 PM




Source: CAISO 2013

Source: Denholm, P., O'Connell, M., Brinkman, G. & Jorgenson, J. *Overgeneration from Solar Energy in California. A Field Guide to the Duck Chart.* (2015). doi:10.2172/1226167




Source: Energy Storage and the California "Duck Curve". Available at: http://large.stanford.edu/courses/2015/ph240/burnett2/ (Accessed: 25th February 2019)

# Status-Quo Solution

Use Storage with Solar and Wind

## New Solution

Overall Idea: We know there is order in chaos. Power systems are complex/chaotic, but potentially with usable chaotic order.

**How can types of chaotic order benefit design?**

Goal: Designed energy system solution incorporates the complexity as a benefit instead of a deficit.

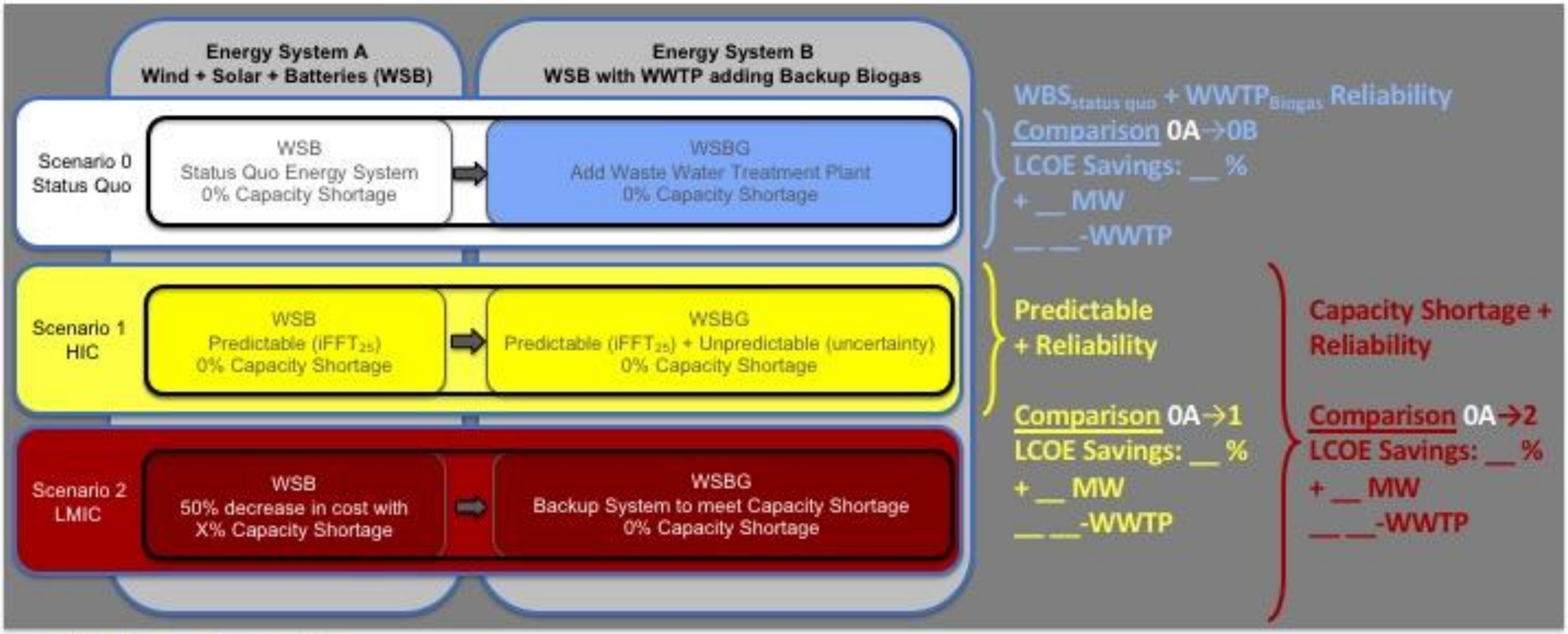
**How can chaotic order be found in this complexity?**

Novel Idea: Focus on HIC and LMIC Energy System Design Assumptions to understand chaotic order.

**Is using chaotic order in assumptions beneficial?**

Fractal by James Ahn

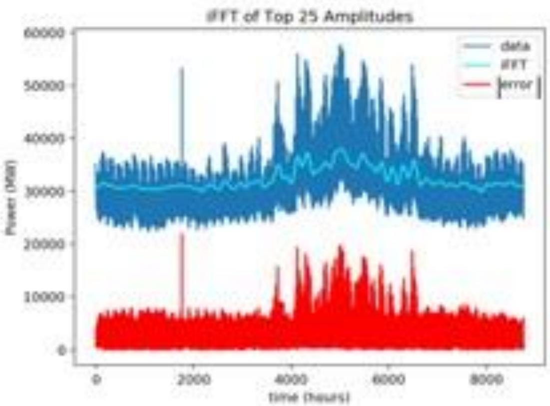
# Design Complexity for Affordability and Reliability



# FFT Analysis in Energy Systems
# City Power Load Example

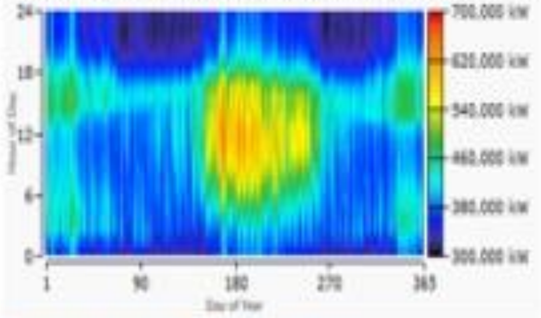
### Three Power versus Time Plots

1 Blue Data - Measured Data Utility
2 Cyan Data - Analyzed Predicted ($iFFT_{25}$)
3 Red Data – Calculated Uncertainty |error|



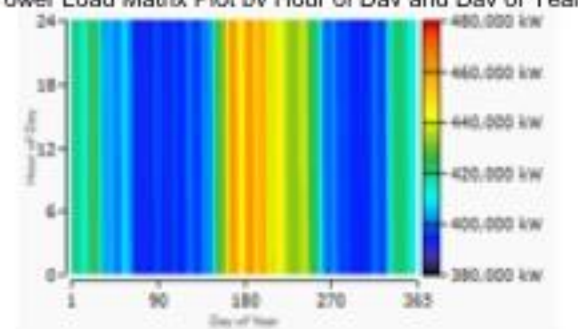

### Measured Utility DMAP

Power Load Matrix Plot by Hour of Day and Day of Year



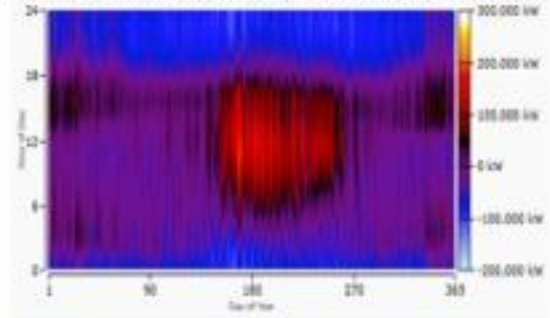

### Analyzed Utility $iFFT_{25}$ DMAP

Power Load Matrix Plot by Hour of Day and Day of Year



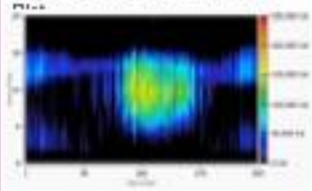

### Calculated Uncertainty DMAP

Power Load Matrix Plot by Hour of Day and Day of Year



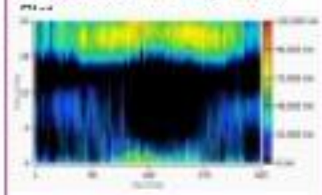

### Positive Uncertainty

Power Load Uncertainty Matrix Plot



### Negative Uncertainty

Power Load Uncertainty Matrix Plot



Applied Energy Symposium

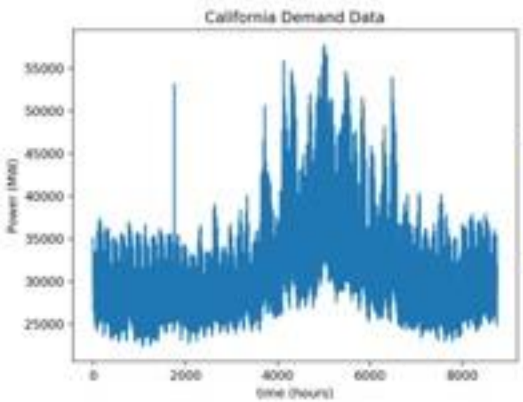
**MIT A+B (AEAB2019)**

# Scenario 1

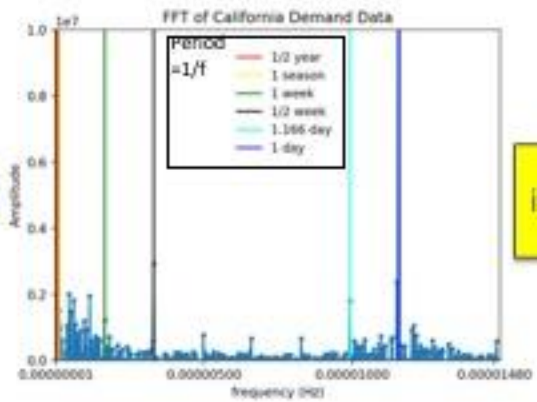
## Example FFT to $iFFT_{25}$ to Uncertainty

### Predictable & Unpredictable

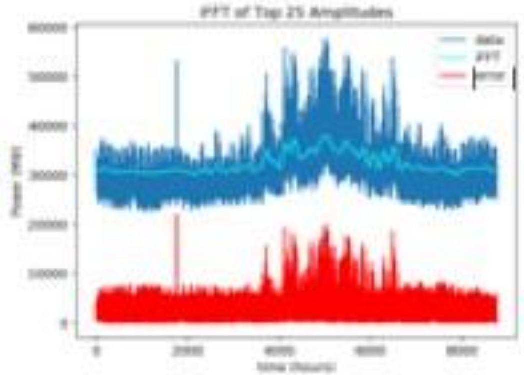
### Example City Data, Analysis, and Calculation











Hour-by-Hour Real Data
EIA-Utility Grid of Region

Python FFT Analysis
Convert Frequency to Period
Take top 25 Amplitudes

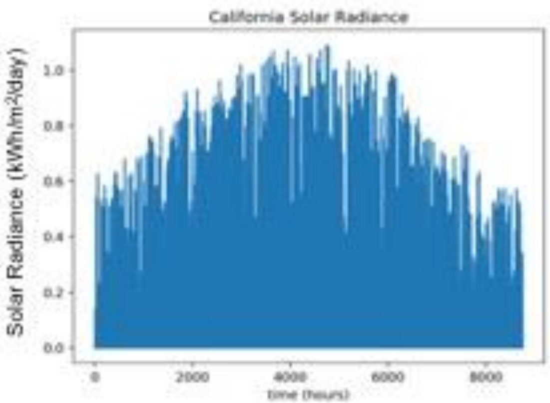
Python inverted FFT Analysis
Calculate Predicted Power Load
Calculate Unpredicted Power Load

# FFT Analysis in Energy Systems
# City Solar Radiance Example



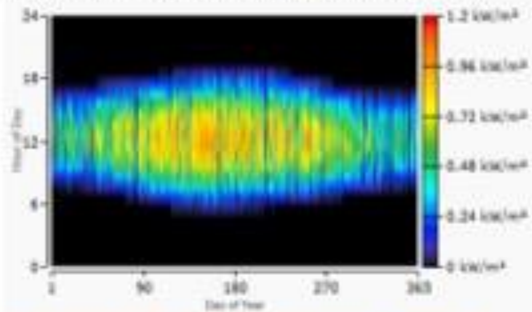
### Three Solar Radiance versus Time Plots

1 Blue Data - Measured Solar Radiance
2 Not shown here – Analyzed Predicted (iFFT$_{25}$)
3 Not shown here– Calculated Uncertainty |error|



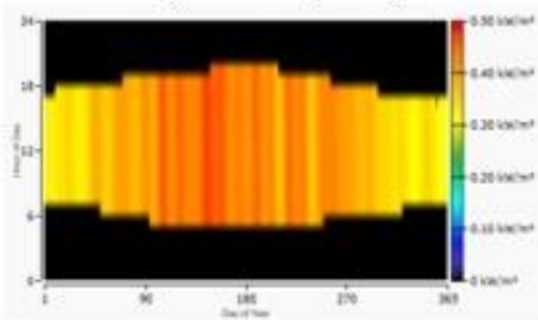

### Measured Solar Intensity DMAP

Solar Matrix Plot by Hour of Day and Day of Year



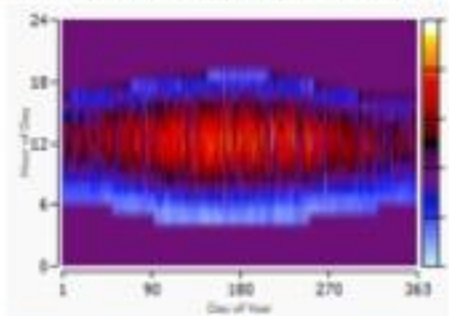

### Analyzed Solar Intensity iFFT$_{25}$ DMAP

Solar Matrix Plot by Hour of Day and Day of Year



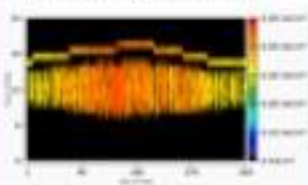

### Calculated Solar Intensity Uncertainty DMAP

Solar Matrix Plot by Hour of Day and Day of Year



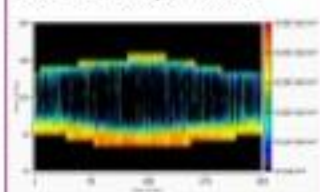

### Positive Uncertainty

Solar Uncertainty Matrix Plot



### Negative Uncertainty

Solar Uncertainty Matrix Plot

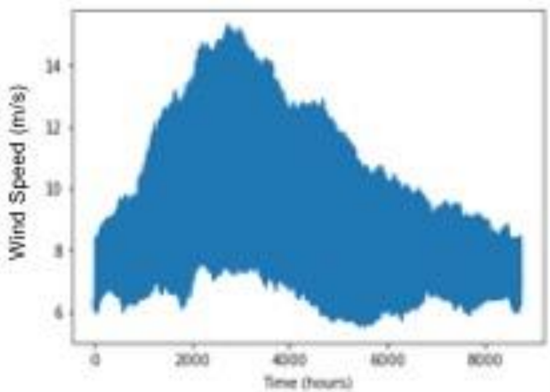


# FFT Analysis in Energy Systems
# City Wind Speed Example



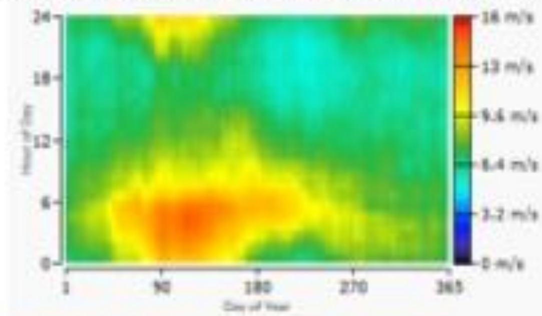
**Three Wind Speed versus Time Plots**

1 Blue Data - Measured Wind Speed
2 Not shown here – Analyzed Predicted (iFFT$_{25}$)
3 Not shown here– Calculated Uncertainty |error|



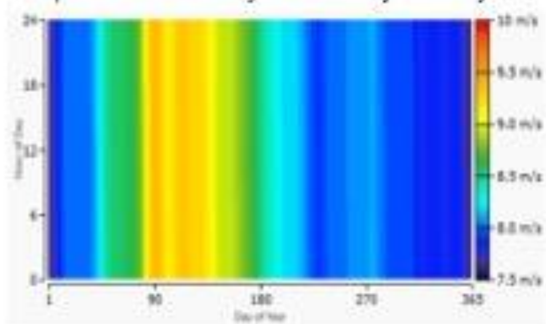

**Measured Wind Speed DMAP**

Wind Speed Matrix Plot by Hour of Day and Day of Year



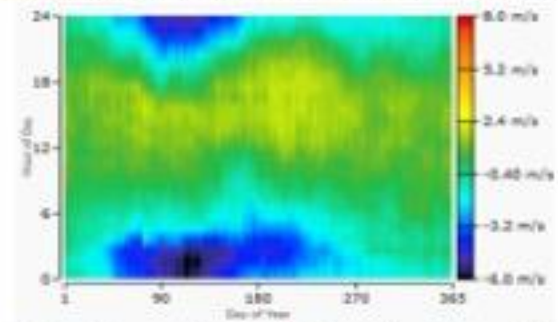

**Analyzed Wind Speed iFFT$_{25}$ DMAP**

Wind Speed Matrix Plot by Hour of Day and Day of Year



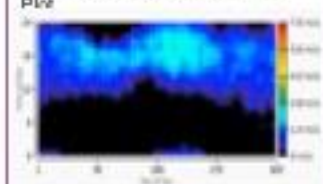

**Calculated Wind Speed Uncertainty DMAP**

Wind Speed Matrix Plot by Hour of Day and Day of Year



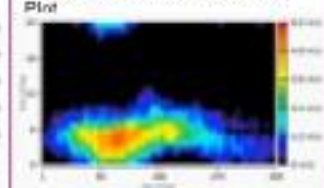

**Positive Uncertainty**

Wind Speed Uncertainty Matrix Plot



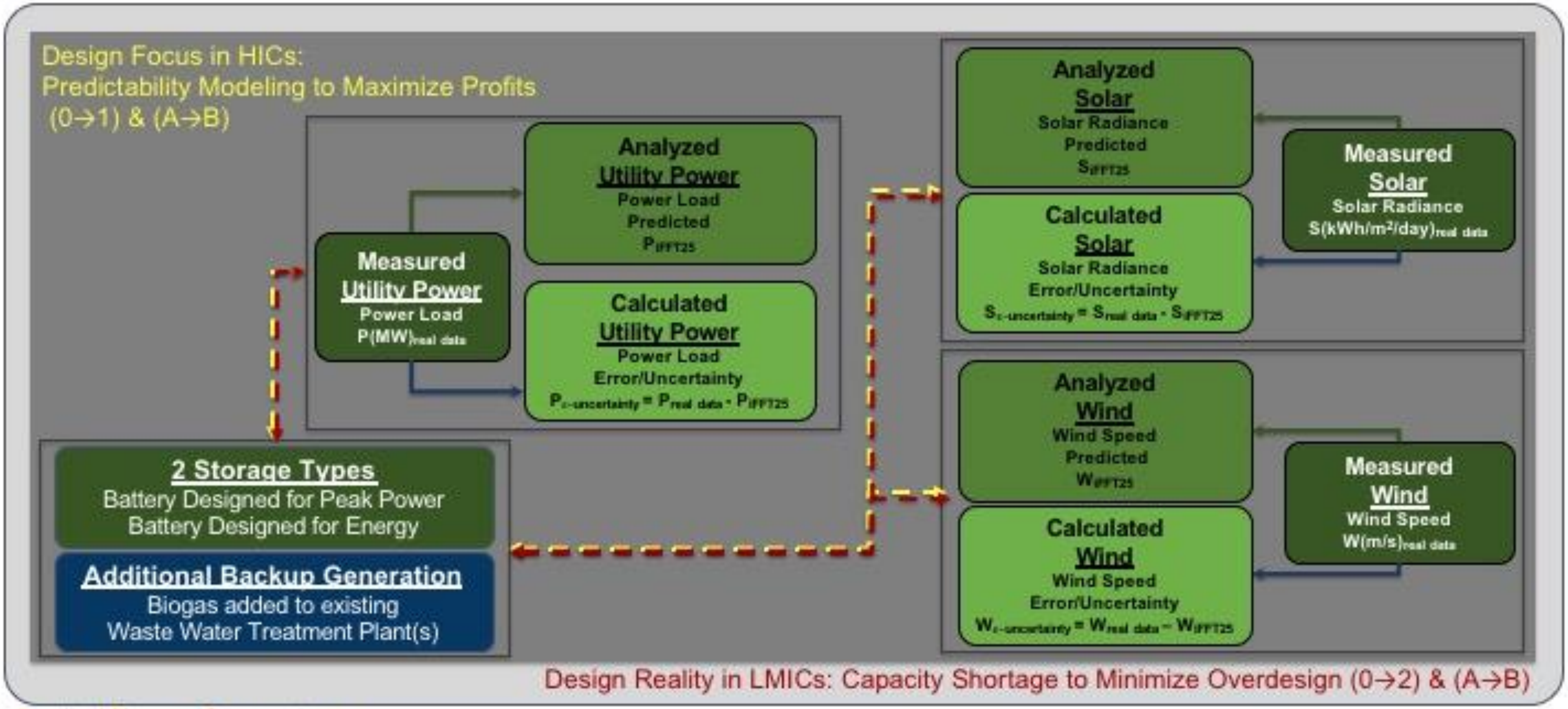
**Negative Uncertainty**

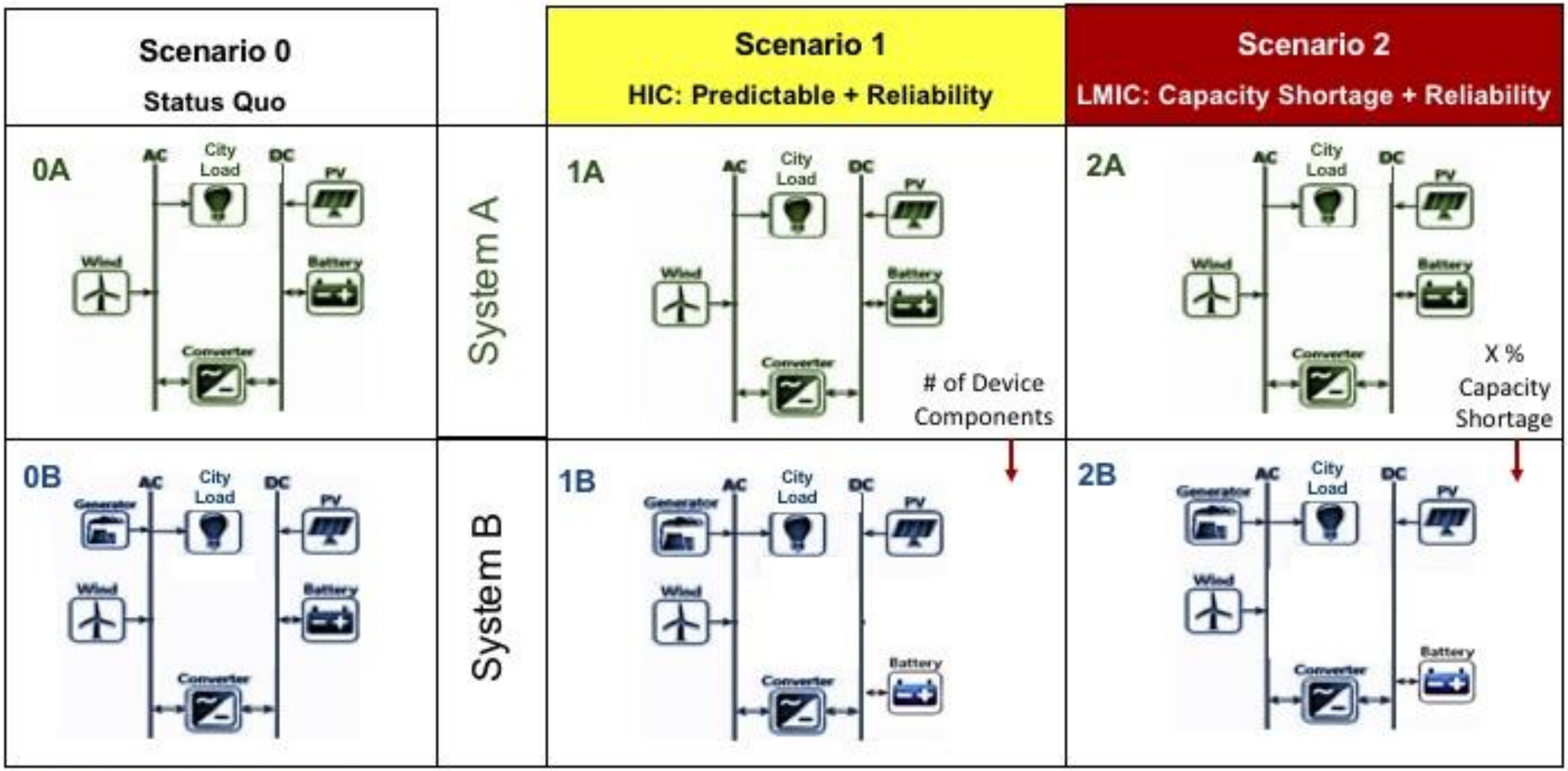
Wind Speed Uncertainty Matrix Plot



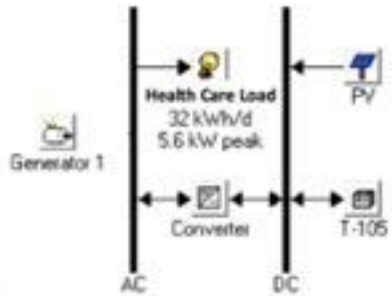
# Flow Chart for Energy Scenario (0-1-2) & System (A+B) Designs



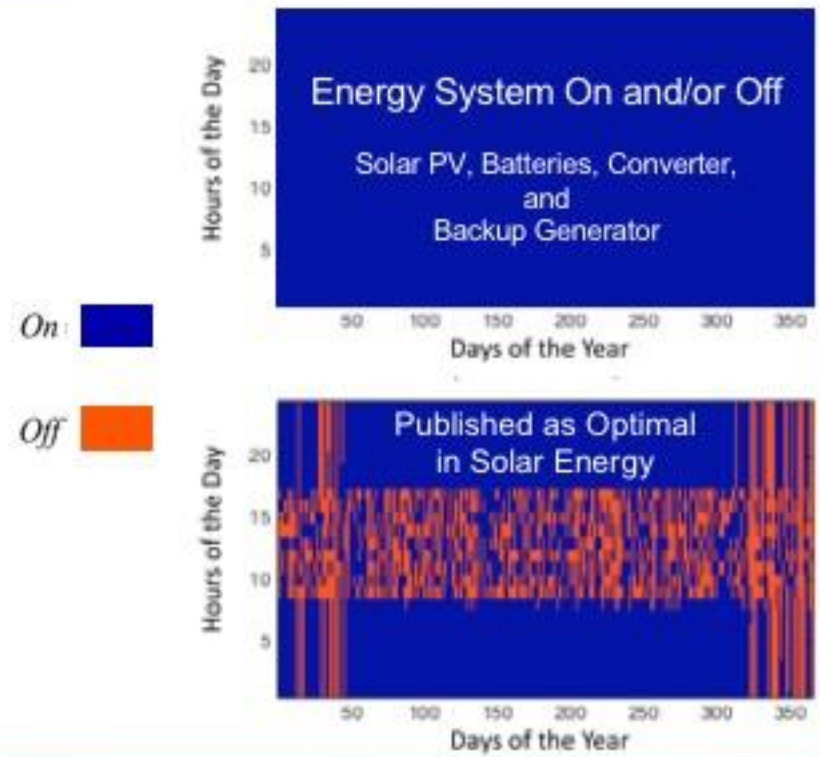



Scenario 0
Status Quo
Scenario 1
HIC: Predictable + Reliability
Scenario 2
LMIC: Capacity Shortage + Reliability
System A
System B
0A
1A
2A
0B
1B
2B
AC
DC
City Load
PV
Wind
Battery
Converter
Generator
# of Device Components
X % Capacity Shortage

# LMIC Reality for Health Care Electricity Systems

| | Iraq - *Solar Energy*, 2010 |
|---|---|
| |  |
| Cost of Electricity ($/kWh) | $0.26/kWh |
| Energy Capacity Shortage (%) $\frac{E_{not\ served}}{E_{load}}$ | 18 % |
| Time Capacity Shortage (%) $\frac{t_{not\ served}}{t_{load}}$ | 25 % |
| Failures (hrs/year) | 2160 hours |
| Back-up System | Install Solar no backup chosen |



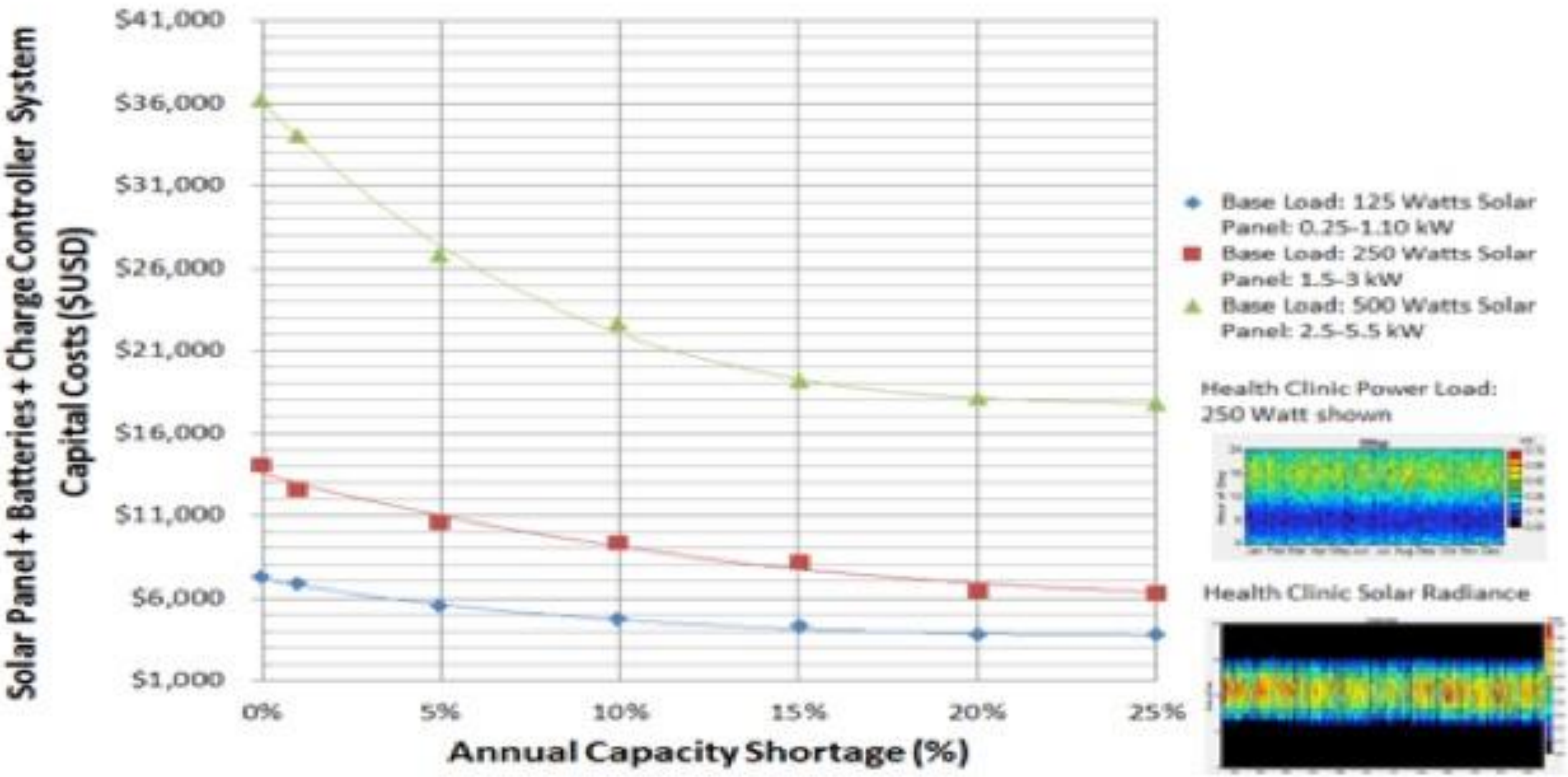



Source: Ali Al-Karaghouli, L.L. Kazmerski, Optimization and life-cycle cost of health clinic PV system for a rural area in southern Iraq using HOMER software, Solar Energy, Volume 84, Issue 4, 2010, Pages 710-714, ISSN 0038-092X.

A Mechtenberg, B McLaughlin, M DiGaetano, A Awodele, M Musaazi, L Nanjula, M Shrime . Impact of electricity failures on health care in terms of hidden costs and risks: A value of statistical life lost divided by

# LMIC - Electricity and Health Care Trade-off






Cost savings of 50% with Reliability for Solar Panels at 80% (called Capacity Shortage).
Back-Up Systems needed only for 20% of the time (life-and-death situations).

Source: Mechtenberg, A.R., Musaazi, M.E., Senabulya, N., & Makanda, J. (2012). Socio-technical implication of renewable energy sources: African health care case study with Monte-Carlo simulations. *2012 IEEE International Symposium on Sustainable Systems and Technology (ISSST)*, 1-6.

# Scenario and Energy System Results

For 100+ US Cities (10+ million data points)

Not most recent result as undergraduate student made a mistake that I am now correcting (really need API to work).

| Scenarios (0-1-2) and Energy Systems (A+B) | Number of Cities where Model is Lowest Levelized Cost of Electricity Optimization Technique Matters ($/kWh) |
|---|---|
| Status-quo WSB: 0A | 4.5% |
| WSB + Adding Biogas$_{WWTP}$: 0B | 9.1 % |
| HIC Assumptions: 1 | 27% |
| LMIC Assumptions: 2 | 59 % |

# Research Question with Results

How can we **better** incorporate renewable energies (RE) into the grid?

Affordably

Reliably

**20% to 50%**
**Costs Savings**
**Affordability**

**0 to 6 L-WWTP**
**Backup Biogas**
**Reliability**

Using complexity of renewable energy as a benefit and not as a deficit…

**Design with RE Complexity**

for increase in likelihood to mitigate and adapt to climate change.

# EMMO Energy $E^3$ Team


Perfect Mfashijwenimana, Albert Maniraho, Sumbusha Etienne, Haguma Christian
Sibomana Moise, Ngendahayo Abel, Hakizimana Francois, Hakizimana Fidele, Etienne Ntagwirumugara

# Reliable-Affordable-Resilient Smart Grids

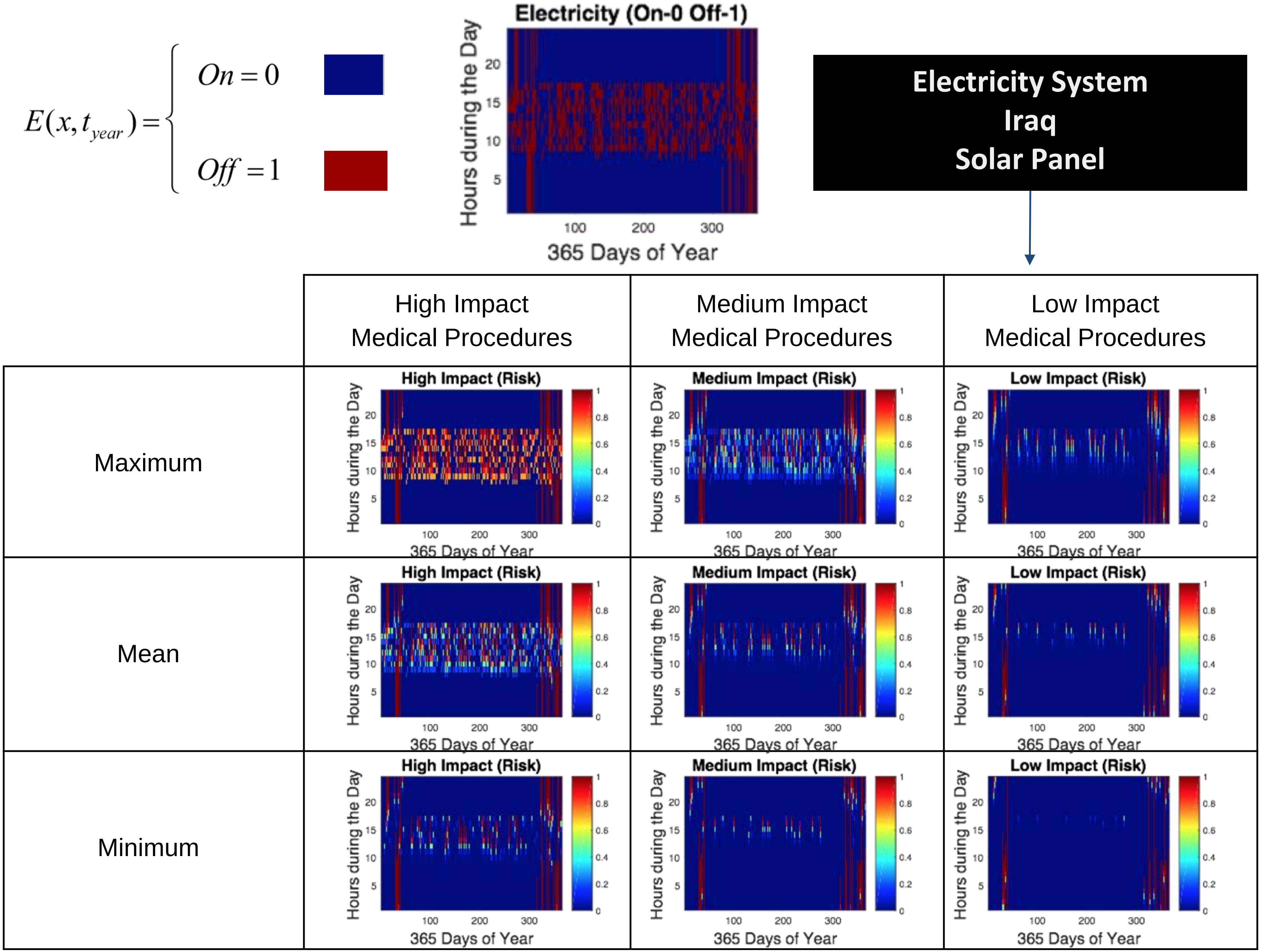
## from United States to Uganda to United Nations

| | |
|---|---|
| Academic Collaborators: | Abigail Mechtenberg*, Mark Shrime, Diane Peters, Manisha Shah, Lanre Olatomiwa, John Makanda, Lydia Nanjula, Manisha Shah, Peter Lating, Moses Musaazi |
| Academic Student Researchers: | Doyinsade Awodele, Janaya Brown, Emmanuel Etwalue, Henri Francois, Kalule Guwatudde, Michael Nweze, Brady McLaughlin, Perfect Mfashijwenimana, Musodiq Ogunlowo, Leslie Omeeboh, Robert Stiller, Anne Stratman |
| Academic Institutions: | University of Notre Dame; Makerere University; University of Rwanda; Institute Haitien de L'Energie; Federal University of Technology, Minna, Nigeria; Mountains of the Moon University; Ugandan Small Scale Industry Association; Uganda Martyrs University; Kettering University, Harvard University |
| Industry Collaborators: | Mulago Hospital, Virika Hospital, Bosch International, Homer Energy |
| Previous Funding: | ND Energy, UM-Michigan Memorial Phoenix Energy Institute, UM-Office of Vice President and Research, UM-African Studies Center, UM-William Davidson Institute, NSF-RCN, Bosch International |



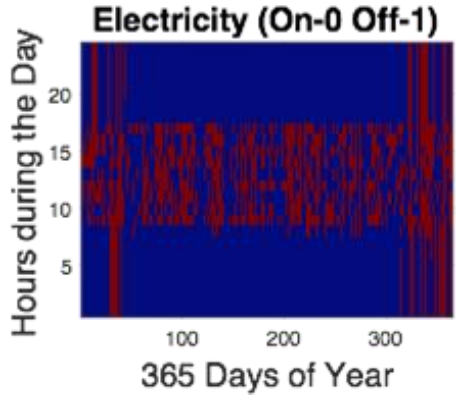
* Today's speaker

# Back-Up Slides

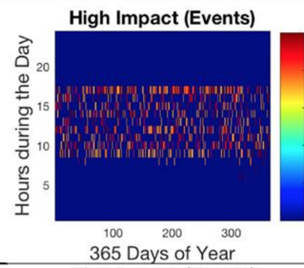
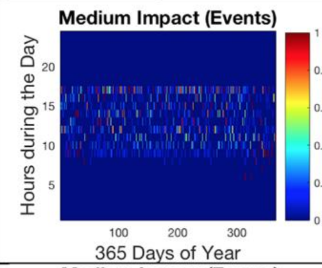
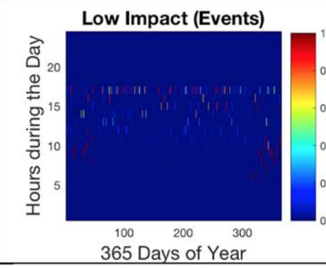
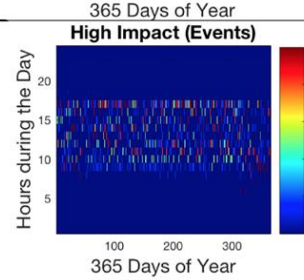
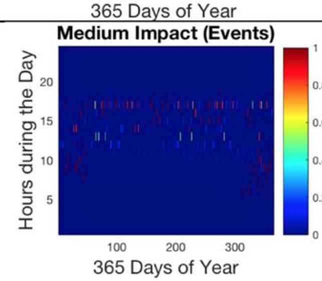
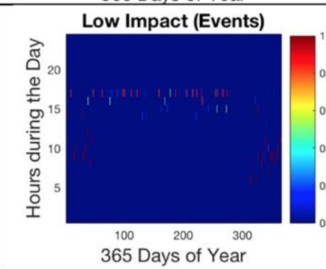
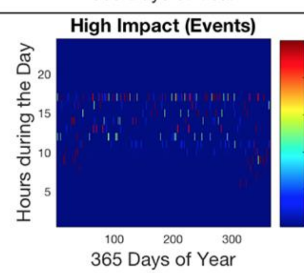
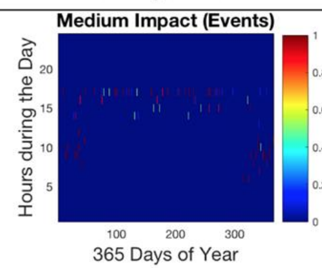
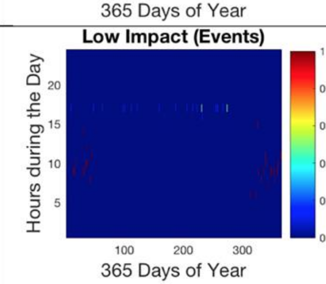


E(x, t_year) = On = 0 / Off = 1
Electricity (On-0 Off-1)
Hours during the Day
365 Days of Year
Electricity System
Iraq
Solar Panel
High Impact Medical Procedures
Medium Impact Medical Procedures
Low Impact Medical Procedures
Maximum
Mean
Minimum
High Impact (Risk)
Medium Impact (Risk)
Low Impact (Risk)

$$E(x, t_{year}) = \begin{cases} On = 0 \\ Off = 1 \end{cases}$$




**Electricity System**
**Iraq**
**Solar Panel**

<table>
<tr><td>Deleting Postponing Procedures</td><td>High Impact Medical Procedures</td><td>Medium Impact Medical Procedures</td><td>Low Impact Medical Procedures</td></tr>
<tr><td>Maximum</td><td>
</td><td>
</td><td>
</td></tr>
<tr><td>Mean</td><td>
</td><td>
</td><td>
</td></tr>
<tr><td>Minimum</td><td>
</td><td>
</td><td>
</td></tr>
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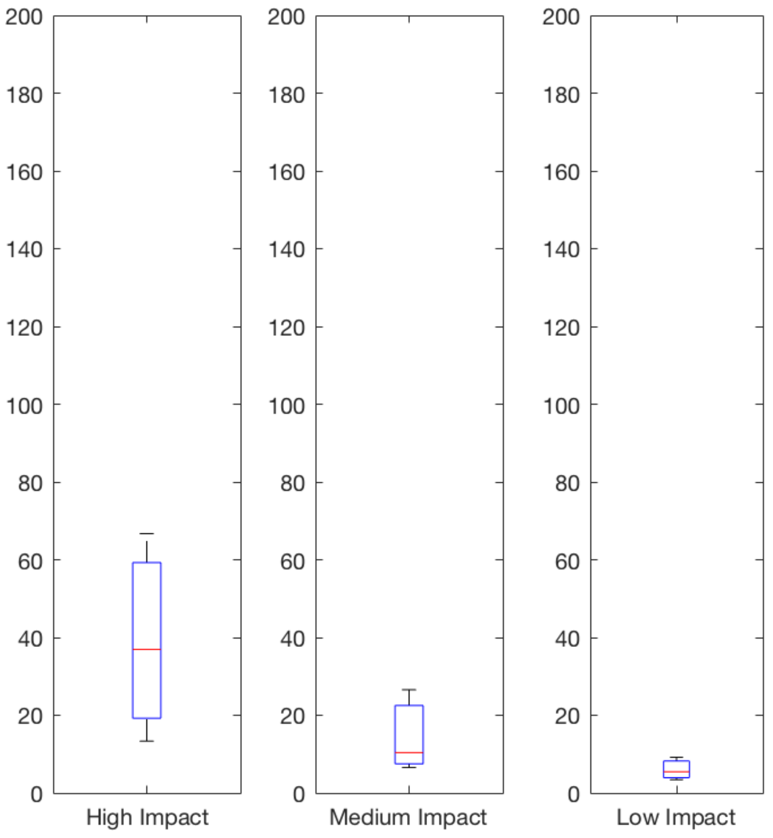
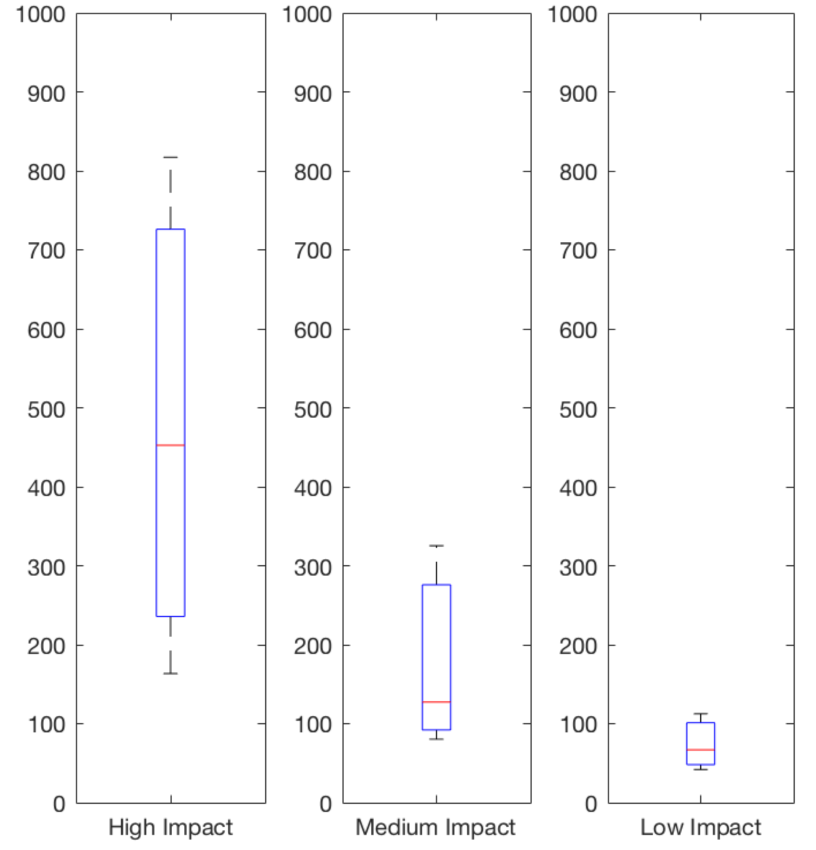
# Solar Powered Health Center

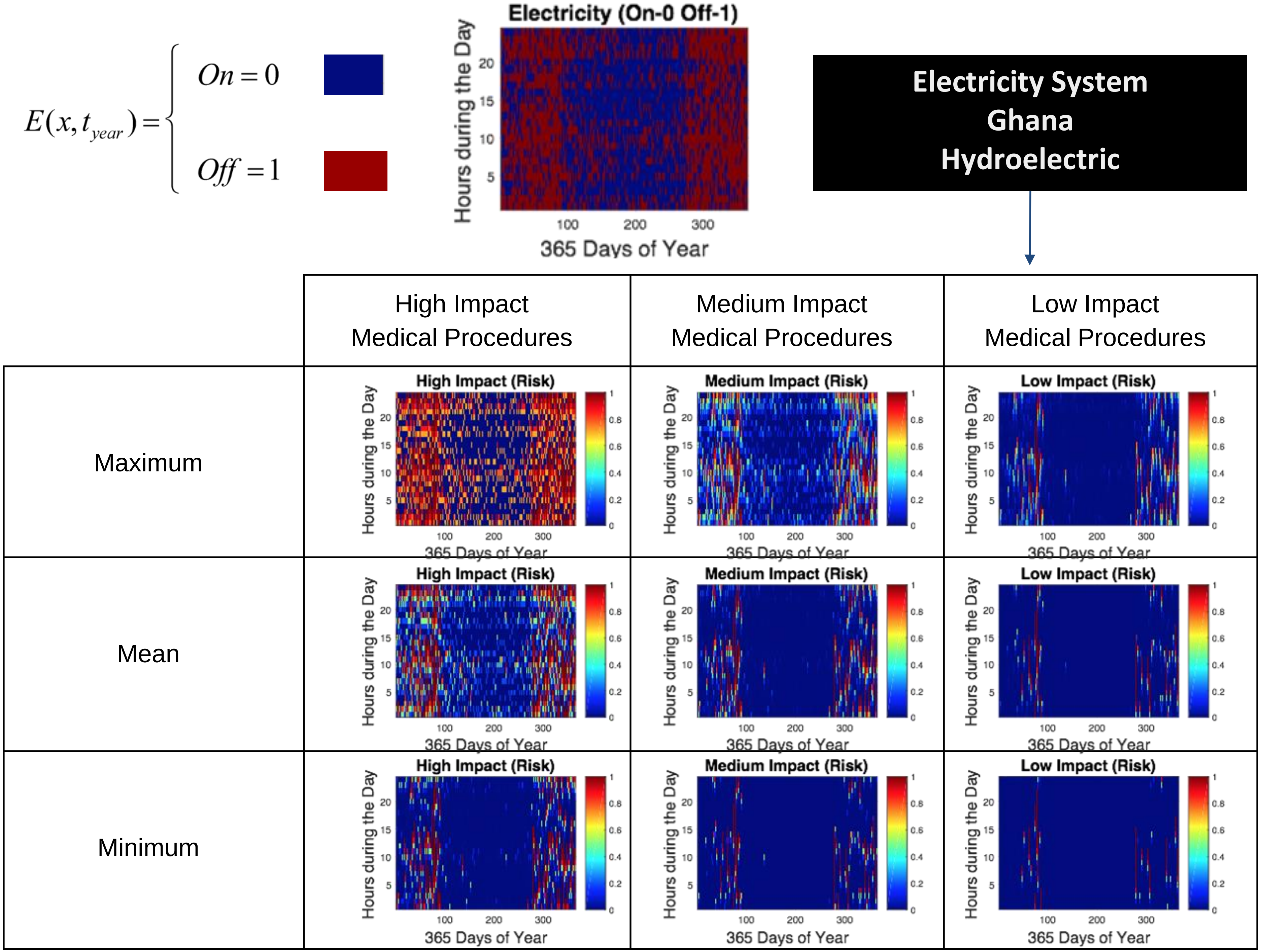
## Patient Deaths per 1,000 over the year of events: 8760 hr




## Patient Deaths per 1,000 over electricity outage events

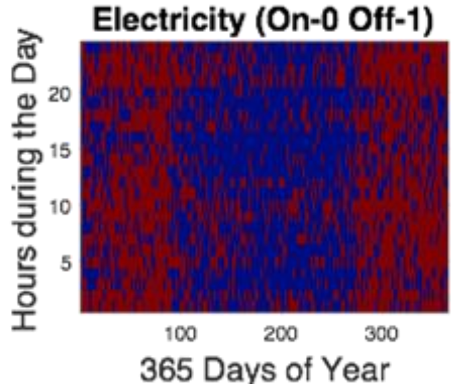



Note: The number of patient deaths per 1,000 over the entire year (electricity on and off events) is small compared to the number of patient deaths per 1,000 for those who experience a failure (only electricity off events) during their medical procedure.

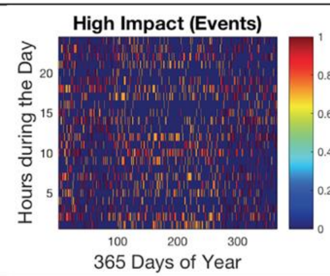
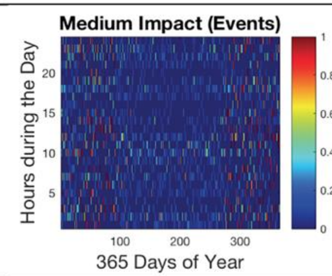
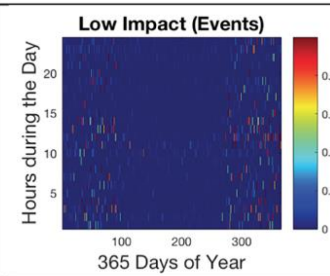
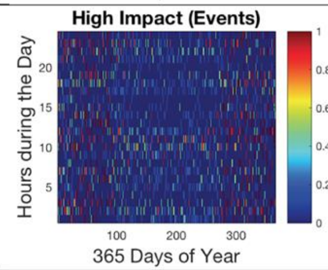
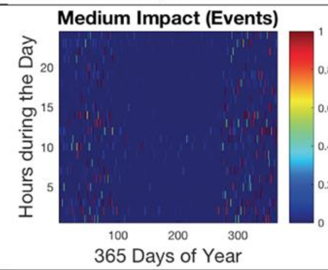
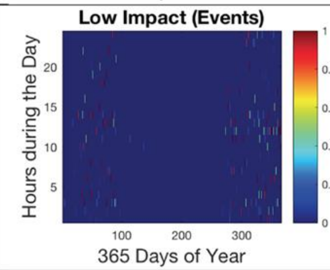
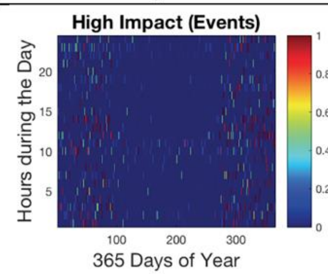
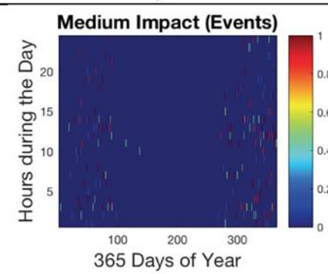
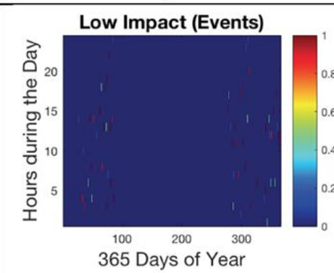


$E(x, t_{year}) = \begin{cases} On = 0 \\ Off = 1 \end{cases}$
Electricity (On-0 Off-1)
Hours during the Day
365 Days of Year
Electricity System
Ghana
Hydroelectric
High Impact
Medical Procedures
Medium Impact
Medical Procedures
Low Impact
Medical Procedures
Maximum
Mean
Minimum
High Impact (Risk)
Medium Impact (Risk)
Low Impact (Risk)

$$E(x, t_{year}) = \begin{cases} On = 0 \\ Off = 1 \end{cases}$$

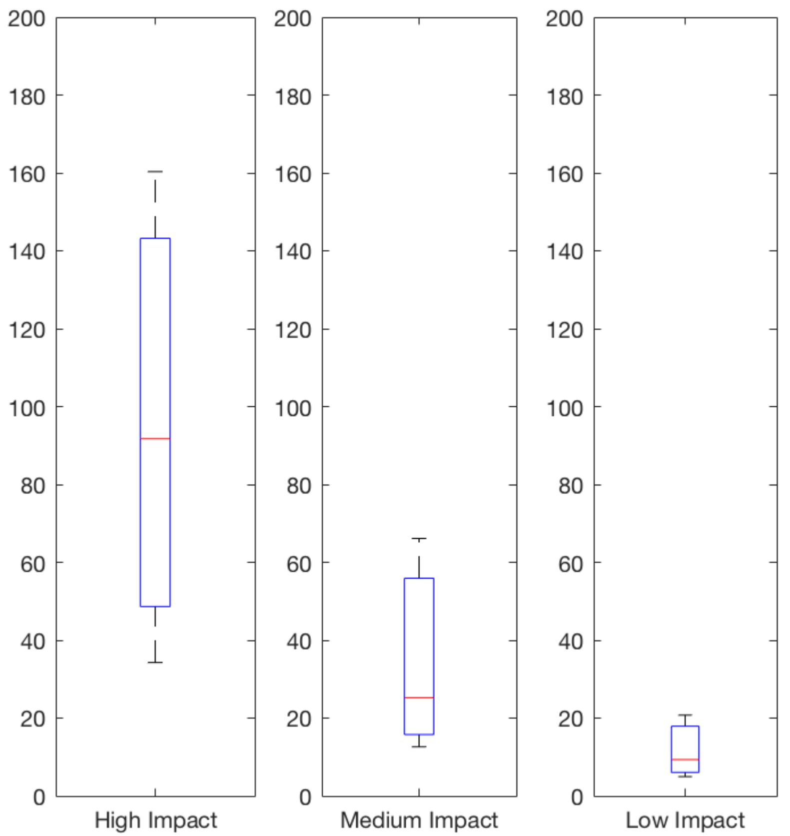



**Electricity System**
**Ghana**
**Hydroelectric**

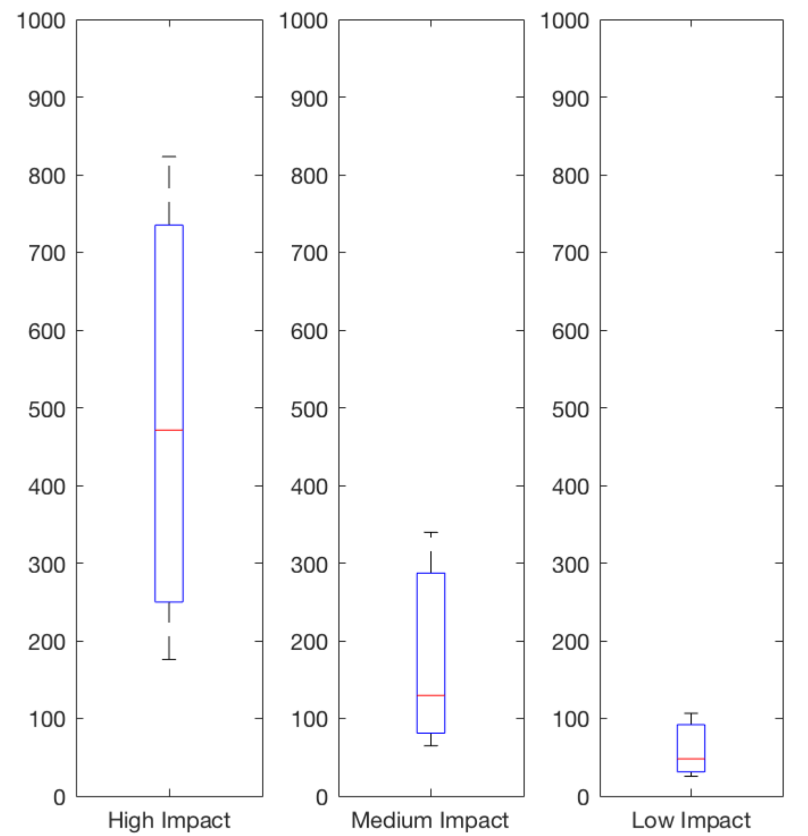
| Deleting Postponing Procedures | High Impact Medical Procedures | Medium Impact Medical Procedures | Low Impact Medical Procedures |
|---|---|---|---|
| Maximum |   |   |   |
| Mean |   |   |   |
| Minimum |   |   |   |

# Hydro Powered Health Center

## Patient Deaths per 1,000 over the entire year

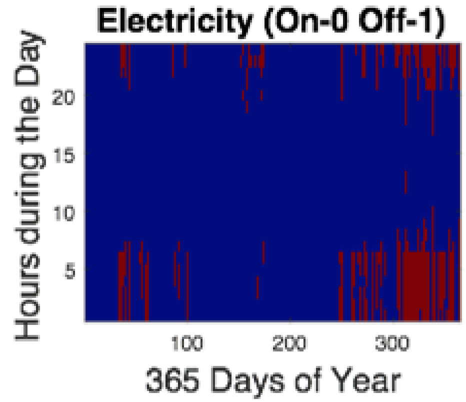



## Patient Deaths per 1,000 over electricity outage events

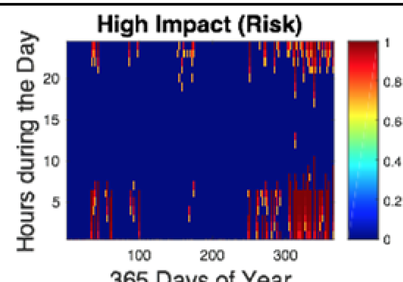
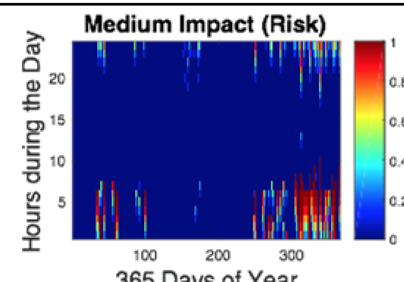
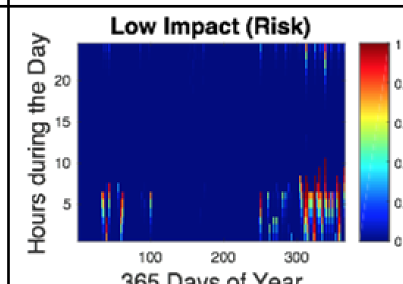
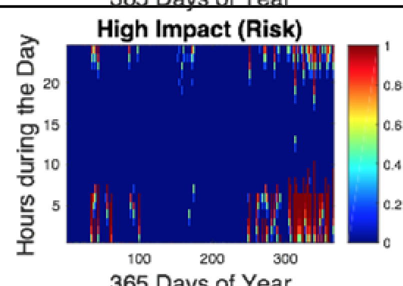
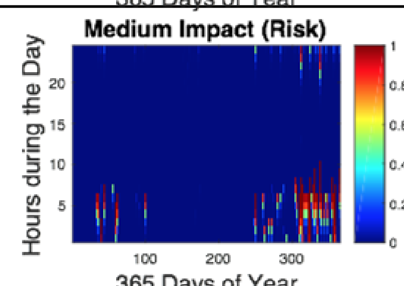
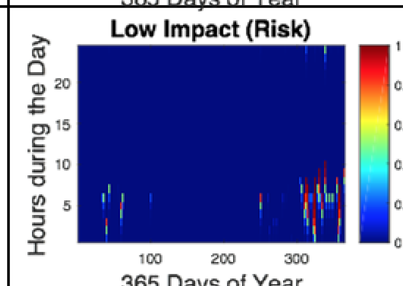
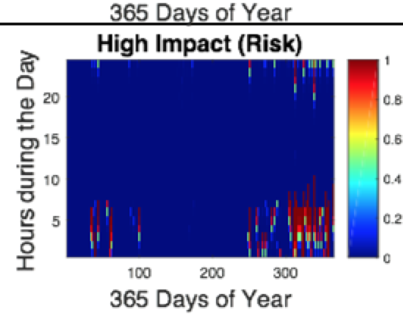
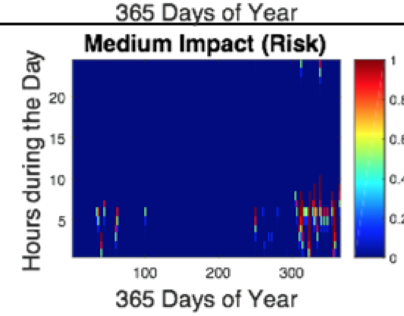
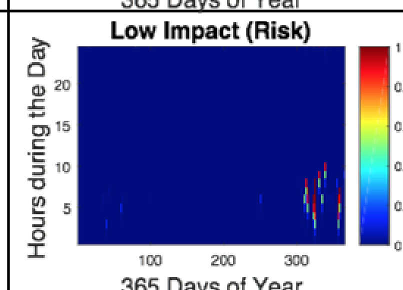



Note: The number of patient deaths per 1,000 over the entire year (electricity on and off events) is small compared to the number of patient deaths per 1,000 for those who experience a failure (only electricity off events) during their medical procedure.

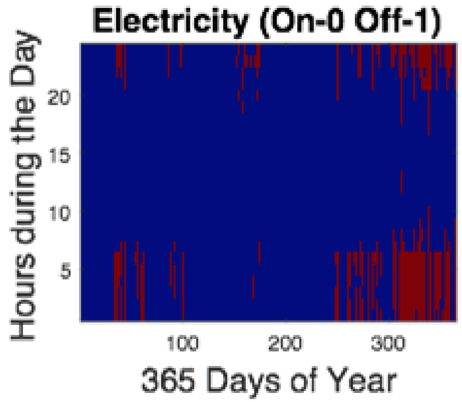
$$E(x, t_{year}) = \begin{cases} On = 0 \\ Off = 1 \end{cases}$$



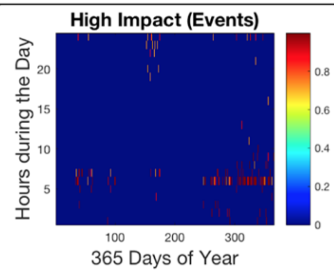
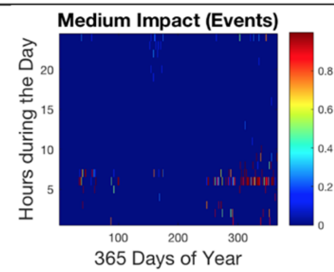
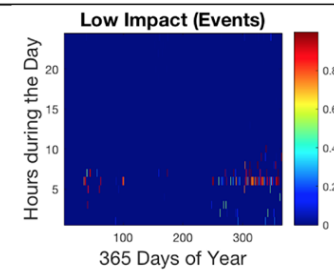
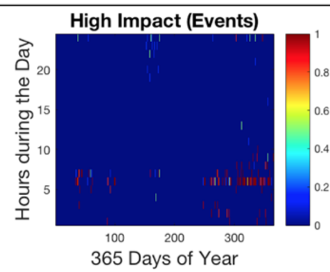
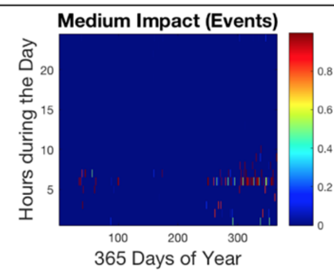
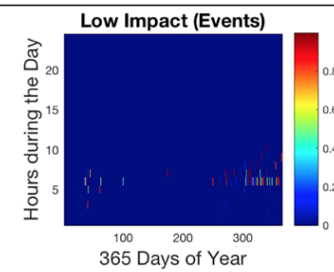
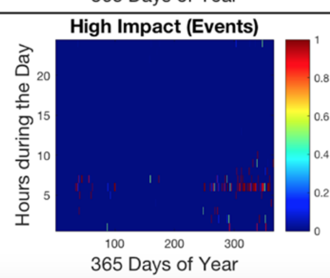
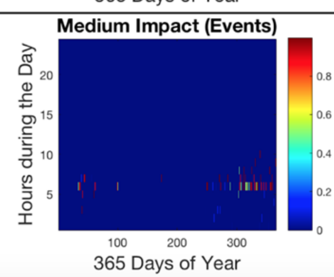
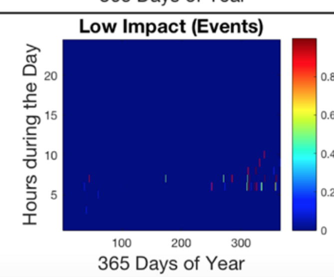

**Electricity System**
**Bangladesh**
**Solar and Wind**

| | High Impact Medical Procedures | Medium Impact Medical Procedures | Low Impact Medical Procedures |
|---|---|---|---|
| Maximum |  |  |  |
| Mean |  |  |  |
| Minimum |  |  |  |

$$E(x,t_{year}) = \begin{cases} On = 0 \\ Off = 1 \end{cases}$$

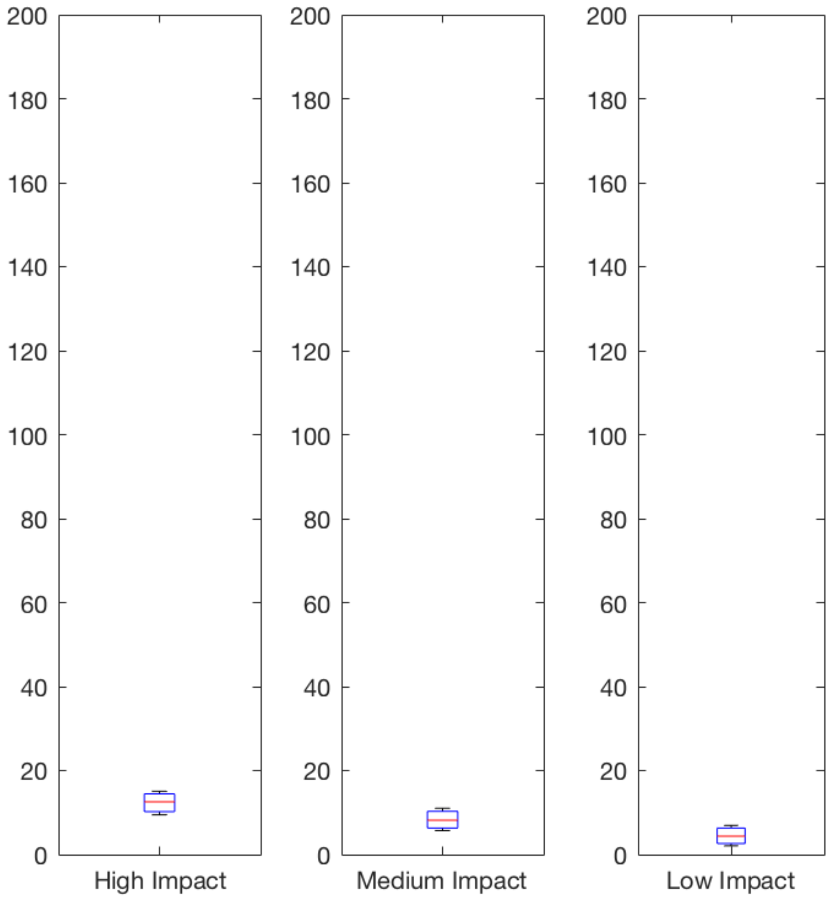



**Electricity System**
**Bangladesh**
**Solar and Wind**

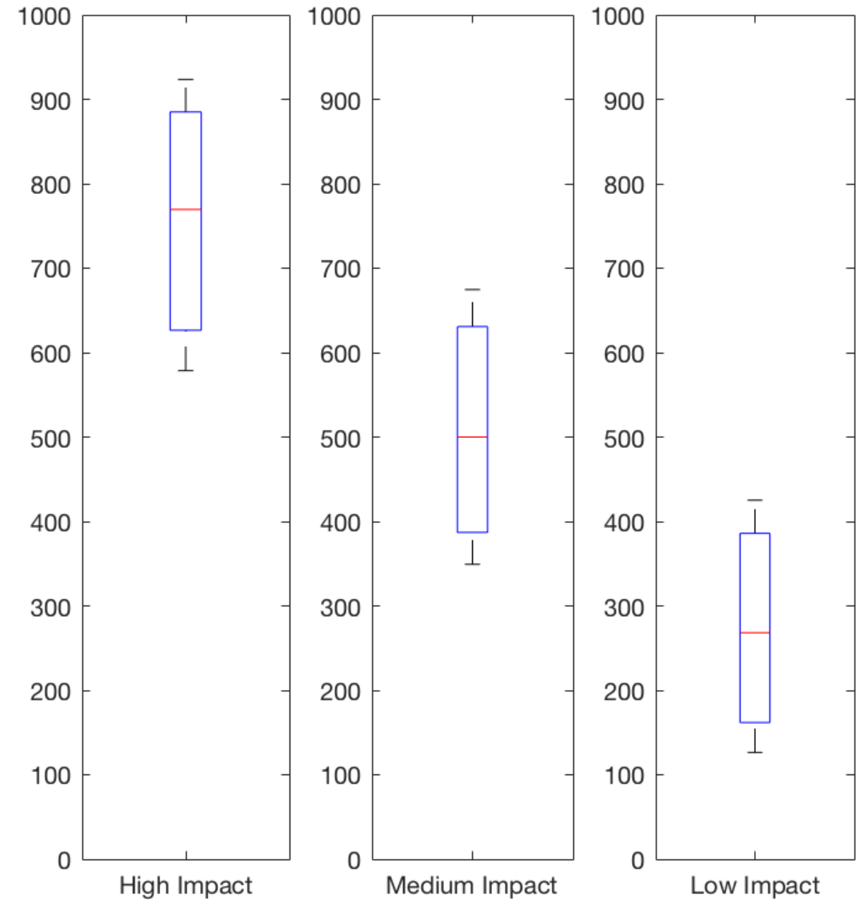
| Deleting Postponing Procedures | High Impact Medical Procedures | Medium Impact Medical Procedures | Low Impact Medical Procedures |
|---|---|---|---|
| Maximum |   |   |   |
| Mean |   |   |   |
| Minimum |   |   |   |

# Solar + Wind Powered Health Center

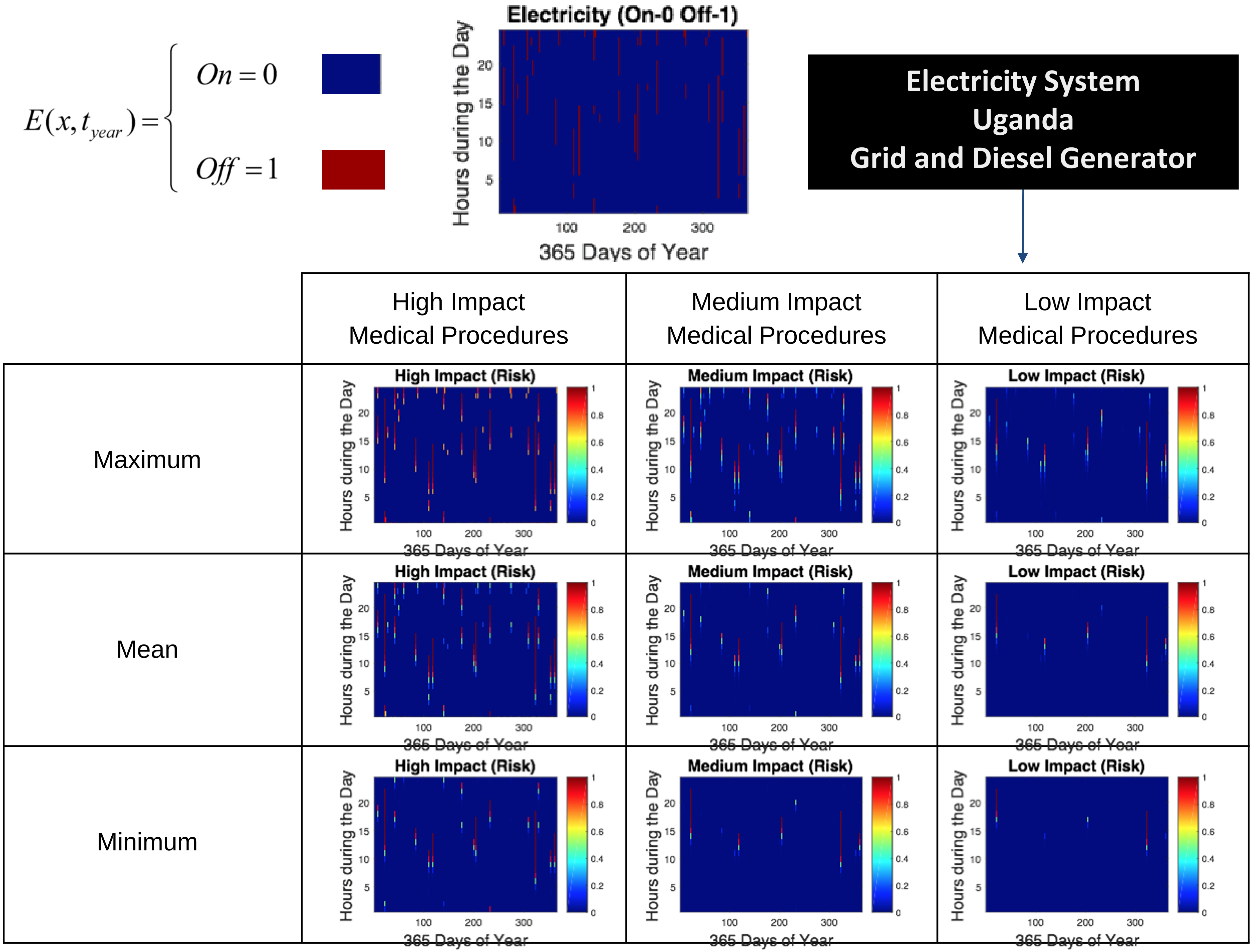
## Patient Deaths per 1,000 over the entire year



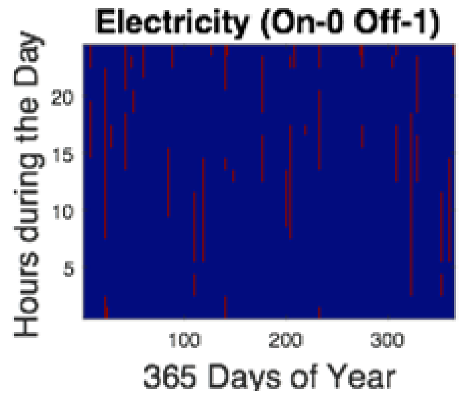

## Patient Deaths per 1,000 over electricity outage events



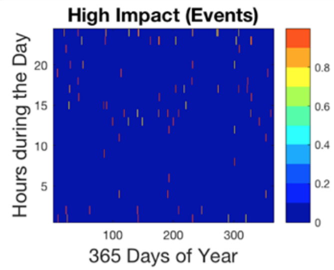
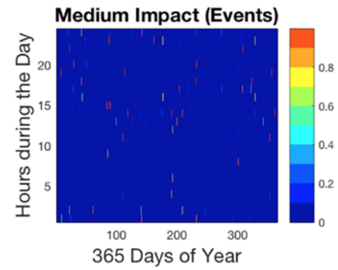
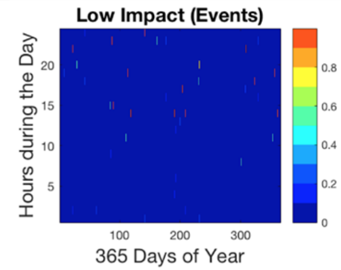
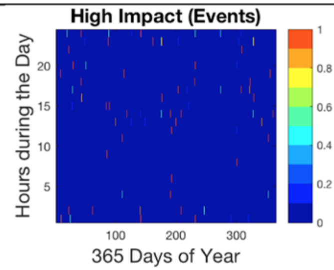
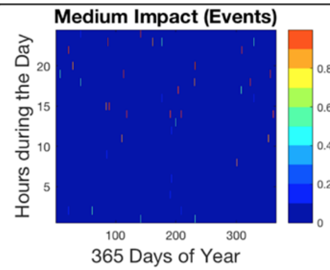
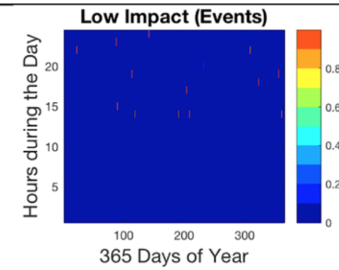

Note: The number of patient deaths per 1,000 over the entire year (electricity on and off events) is small compared to the number of patient deaths per 1,000 for those who experience a failure (only electricity off events) during their medical procedure.


$E(x, t_{year}) = \begin{cases} On = 0 \\ Off = 1 \end{cases}$
Electricity (On-0 Off-1)
Hours during the Day
365 Days of Year
Electricity System
Uganda
Grid and Diesel Generator
High Impact Medical Procedures
Medium Impact Medical Procedures
Low Impact Medical Procedures
Maximum
Mean
Minimum
High Impact (Risk)
Medium Impact (Risk)
Low Impact (Risk)

$$E(x, t_{year}) = \begin{cases} On = 0 \\ Off = 1 \end{cases}$$




**Electricity System**
**Uganda**
**Grid and Diesel Generator**

<table>
<tr><td>Deleting<br>Postponing<br>Procedures</td><td>High Impact<br>Medical Procedures</td><td>Medium Impact<br>Medical Procedures</td><td>Low Impact<br>Medical Procedures</td></tr>
<tr><td>Maximum</td><td>
</td><td>
</td><td>
</td></tr>
<tr><td>Mean</td><td>
</td><td>
</td><td>
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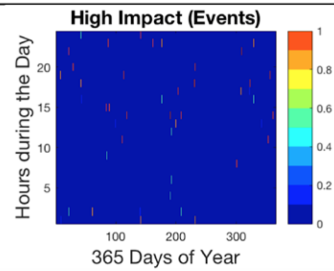
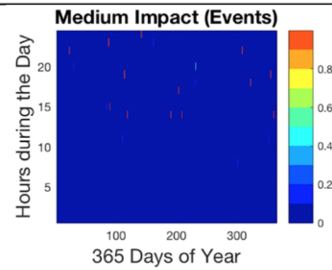
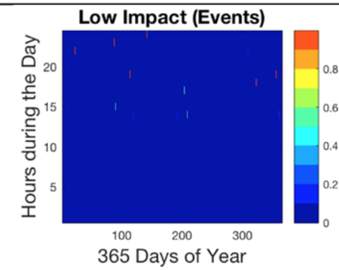
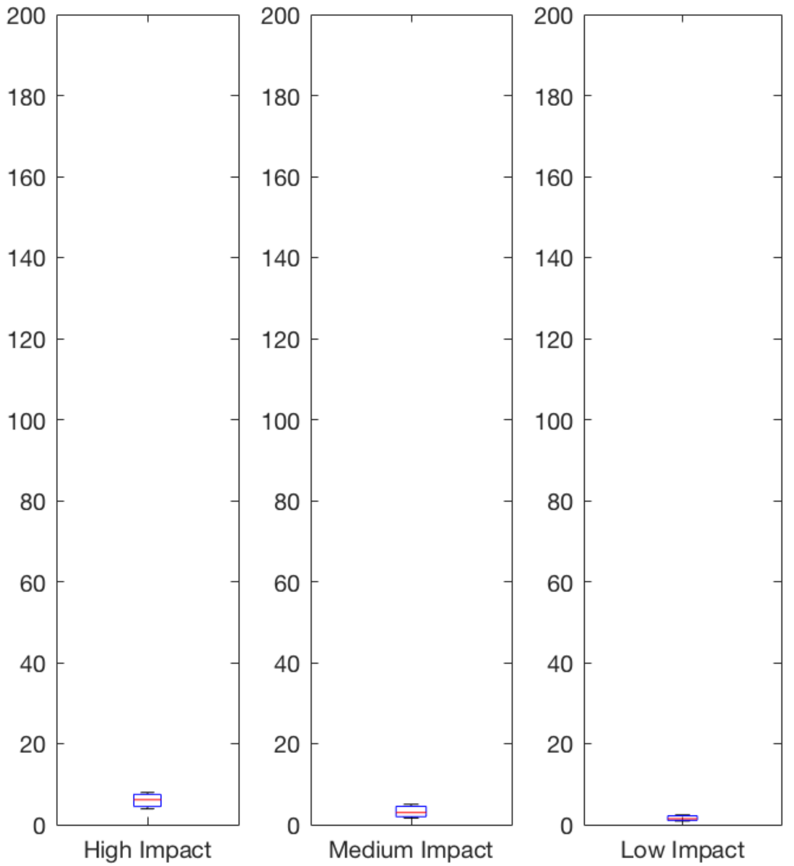
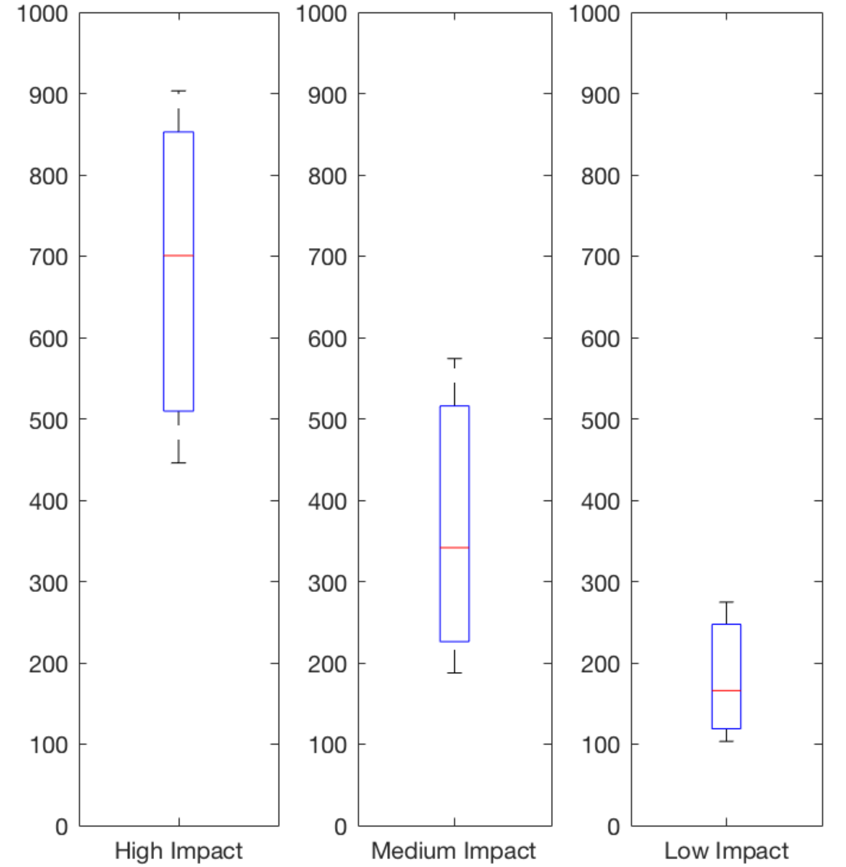
<tr><td>Minimum</td><td>
</td><td>
</td><td>
</td></tr>
</table>

# Grid+Diesel Powered Health Center

## Patient Deaths per 1,000 over the entire year




## Patient Deaths per 1,000 over electricity outage events



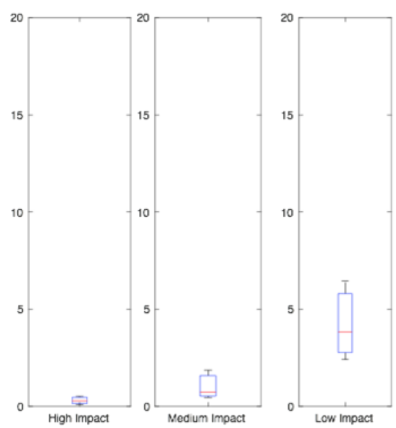

Note: The number of patient deaths per 1,000 over the entire year (electricity on and off events) is small compared to the number of patient deaths per 1,000 for those who experience a failure (only electricity off events) during their medical procedure.

# Small Health Care Facility

## Total: 780 patients per year

1% High Impact, 9% Medium Impact, 70% Low Impact, 20% No Impact

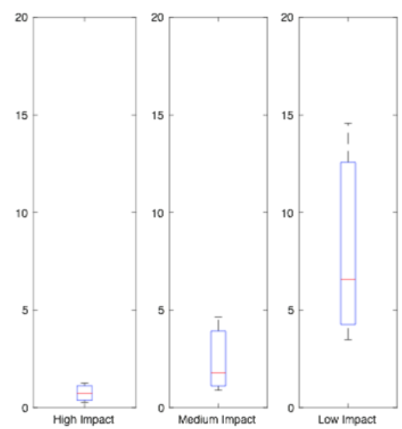
### Modeled Patient Deaths for Specific Facilities




**Solar Only**

5/780 = 0.6 %

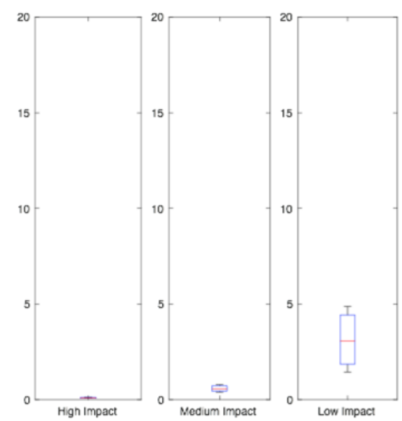
Chance of Death




**Hydro Only**

9/780 = 1.2 %

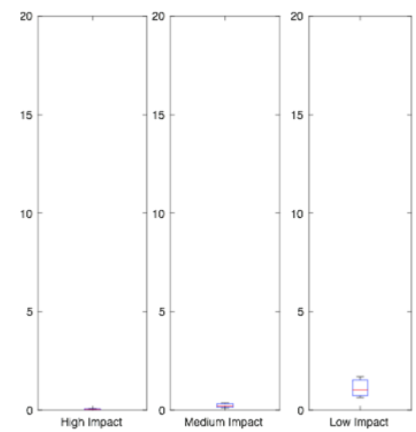
Chance of Death




**Solar+Wind**

4/780 = 0.5 %

Chance of Death




**Grid+Diesel**

1/780 = 0.1 %

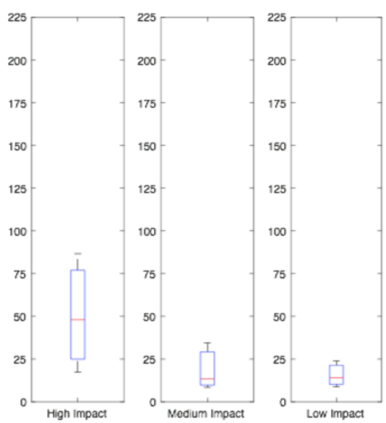
Chance of Death

# Larger Health Care Facility

Total: 5200 patients per year

20% High Impact, 25% Medium Impact, 35% Low Impact, 20% No Impact

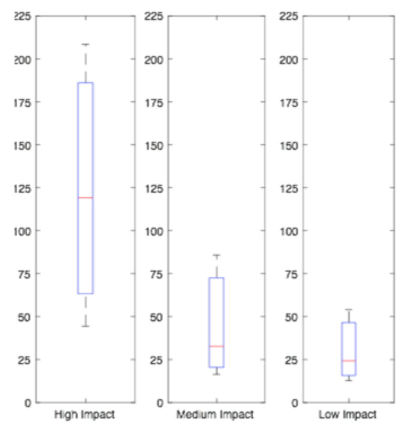
Modeled Patient Deaths for Specific Facilities




**Solar Only**

76/5200 = 1.5 %

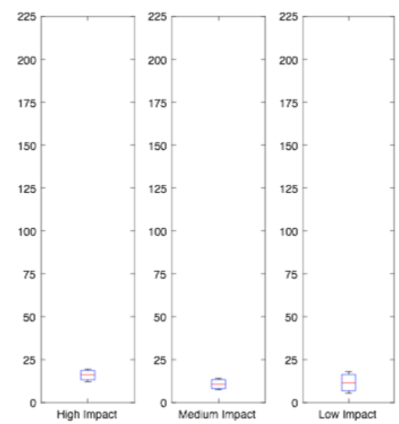
Chance of Death




**Hydro Only**

176/5200 = 3.4 %

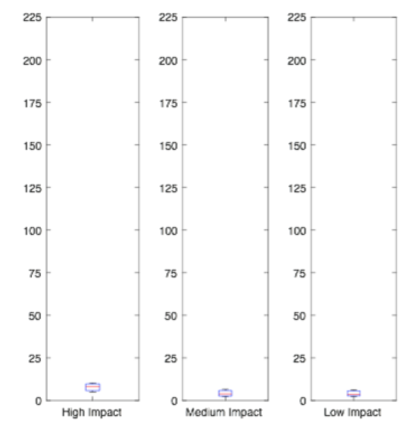
Chance of Death




**Solar+Wind**

38/5200 = 0.7 %

Chance of Death




**Grid+Diesel**

16/5200 = 0.3 %

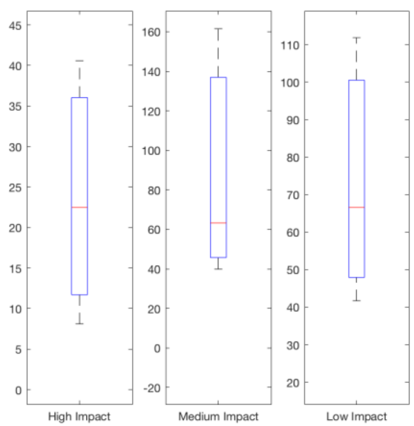
Chance of Death

# Regional Hospital - Not Referral

## Total: 500 hospital beds → 60,833 patients/year

1% High Impact, 10% Medium Impact, 20% Low Impact, 69% No Impact

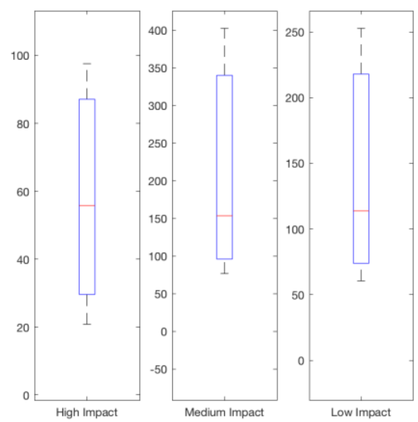
### Modeled Patient Deaths for Specific Facilities




**Solar Only**

153 → 0.3 %

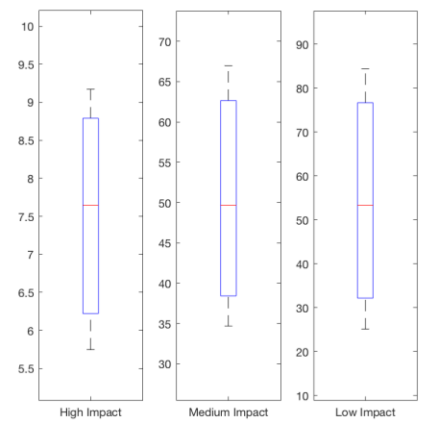
Chance of Death




**Hydro Only**

323 → 0.5 %

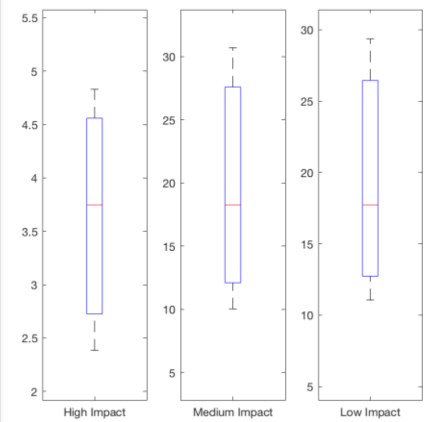
Chance of Death




**Solar+Wind**

110 → 0.2 %

Chance of Death




**Grid+Diesel**

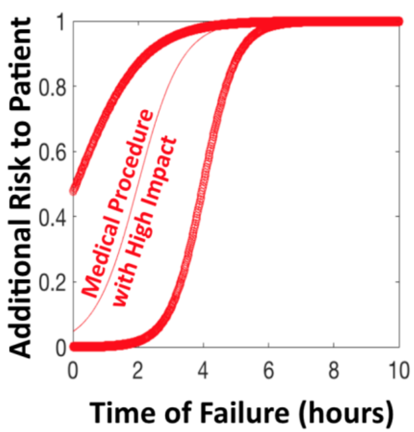
40 → 0.1 %

Chance of Death

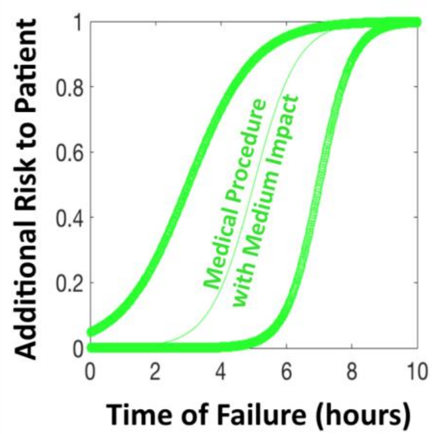
$(k_j, c_i)$

$$r_{ij}(t_{failure}) = \frac{1}{1+\exp(-k_j(t_{failure} - c_i))}$$

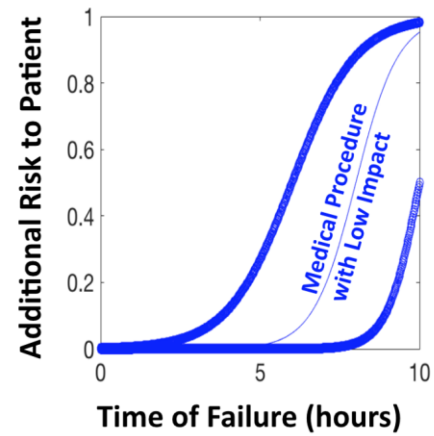
| $k_{High}, c_{1\text{-}i}$ | $k_{Med}, c_{2\text{-}i}$ | $k_{Low}, c_{3\text{-}i}$ |
|---|---|---|
| (1, 0.1) | (1.5, 2) | (2, 4) |
| (1, 3.0) | (1.5, 5) | (2, 7) |
| (1, 6.0) | (1.5, 8) | (2, 10) |




$$r_{High}(t) = \frac{1}{1+\exp(-(t - c_{123}))}$$

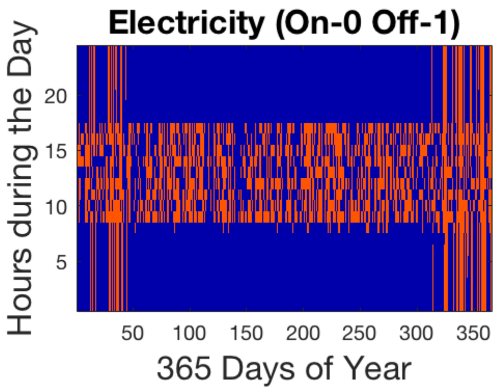


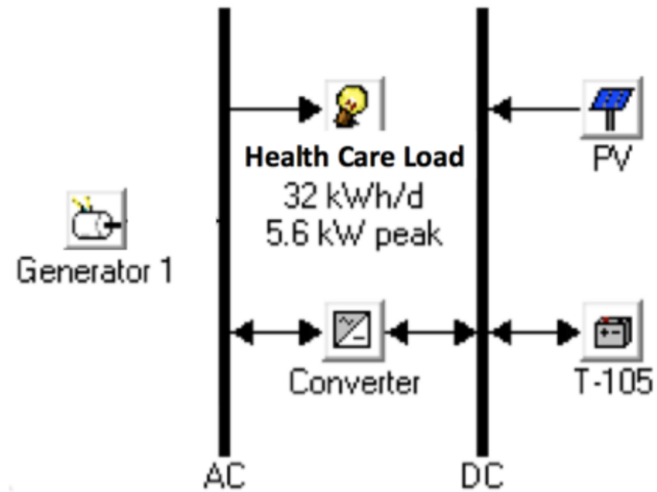

$$r_{Med}(t) = \frac{1}{1+\exp(-1.5(t - c_{123}))}$$



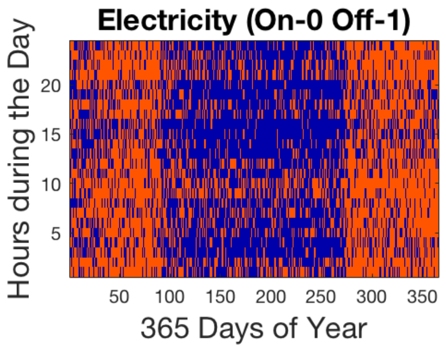

$$r_{Low}(t) = \frac{1}{1+\exp(-2(t - c_{123}))}$$

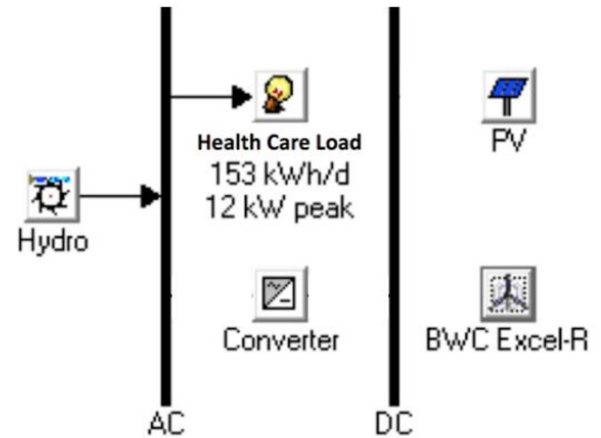
**Note:** six other probabilistic two parameter functions modeled as well. Ask for more details - simulation model is flexible!



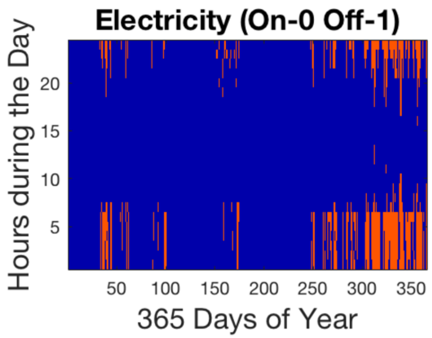

| | Iraq - *Solar Energy*, 2010<br><br> |
|---|---|
| Cost of Electricity ($/kWh) | $0.26/kWh |
| Energy Capacity Shortage (%) $\frac{E_{not\ served}}{E_{total}}$ | 18 % |
| Time Capacity Shortage (%) $\frac{t_{not\ served}}{t_{total}}$ | 25 % |
| Failures (hrs/year) | 2160 hours |
| Back-up System | Install Solar<br>no backup chosen |

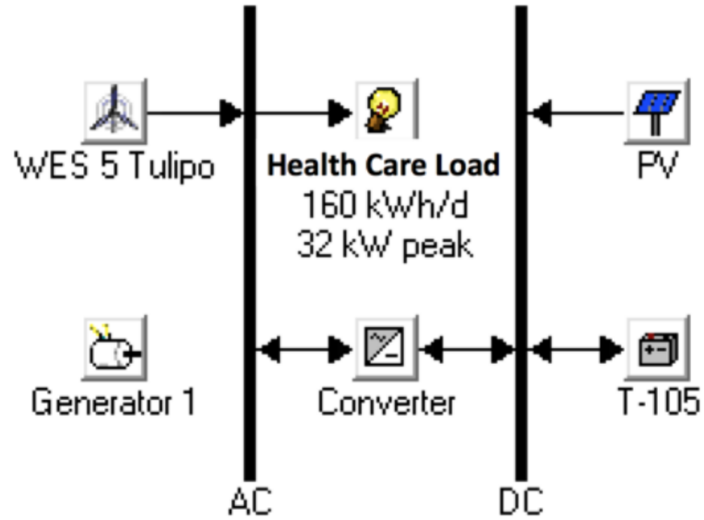
Country: Iraq – Optimal energy system was chosen as solar panel and batteries.



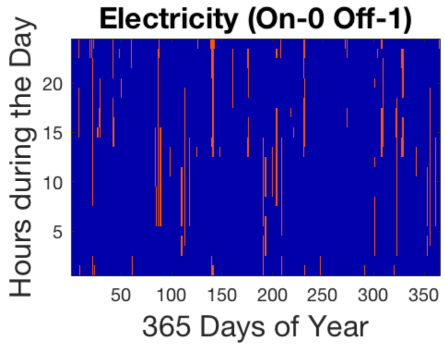

| | Ghana - *International Journal of Computer Applications*, 2015   |
|---|---|
| Cost of Electricity ($/kWh) | $0.12/kWh |
| Energy Capacity Shortage (%) $\frac{E_{not\ served}}{E_{total}}$ | 11 % |
| Time Capacity Shortage (%) $\frac{t_{not\ served}}{t_{total}}$ | 49 % |
| Failures (hrs/year) | 4289 hours |
| Back-up System | Government Grid: Hydro base power, Facilities: Provide their own peak power |

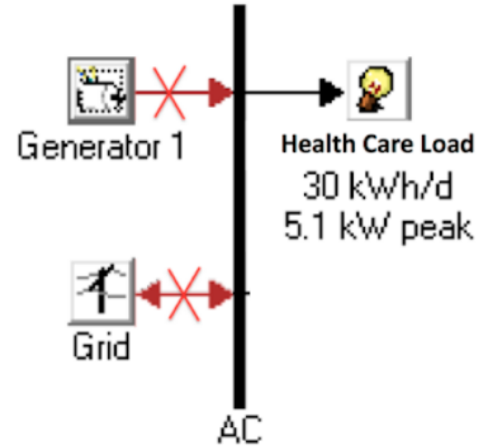
Country: Ghana – Optimal energy system was chosen as hydroelectricity




| | Bangladesh - *Energy*, 2010   |
|---|---|
| Cost of Electricity ($/kWh) | $0.51/kWh |
| Energy Capacity Shortage (%) $\frac{E_{not\ served}}{E_{total}}$ | 10 % |
| Time Capacity Shortage (%) $\frac{t_{not\ served}}{t_{total}}$ | 6.6 % |
| Failures (hrs/year) | 574 hours |
| Back-up System | Install Solar+Wind<br>no backup chosen |

Country: Bangladesh – Optimal energy system was chosen as solar panel and wind.




| | Uganda - *ISSST-IEEE*, 2012<br><br> |
|---|---|
| Cost of Electricity ($/kWh) | Grid: $0.25/kWh - Diesel: $0.75-11/kWh |
| Energy Capacity Shortage (%) $\frac{E_{not\ served}}{E_{total}}$ | 4.1 % |
| Time Capacity Shortage (%) $\frac{t_{not\ served}}{t_{total}}$ | 4.0 % |
| Failures (hrs/year) | 355 hours |
| Back-up System | Year of Data on Voltage and Current Grid+Diesel Generator |

Country: Uganda – Measurements on Grid, Diesel Generator, and Battery System

# Energy $E^3$ - Talk Outline

1. **Health Care Context**
5. **Health Care Hidden Costs**

2. **Energy $E^3$ <u>Uganda</u>**
   **Energy Education, Engineering Design, & Entrepreneurship**

3. **Energy $E^3$ <u>United States</u>**
   **Energy Education, Engineering Design, & Entrepreneurship**

4. **<u>Propagation Model</u>**
   **Uganda Energy $E^3$ Innovation Centers**
   **US Energy $E^3$ Vocational Education**

**Image Credit:**
United Nations Development Program - Sustainable Energy for All Forum Logo, 2018
https://www.seforall.org/content/first-round-speakers-announced-2017-seforall-forum

# Energy E[3] Innovation

Changing Design Paradigm

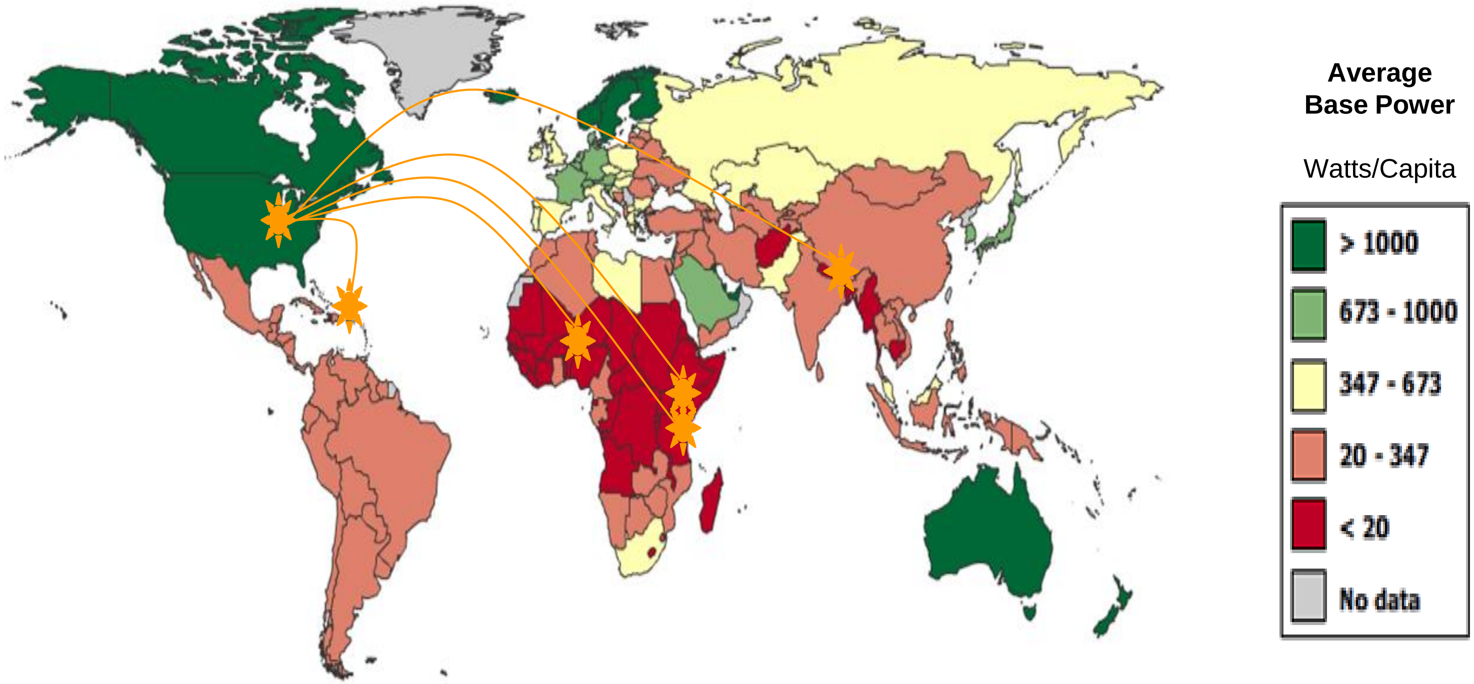
STOP **Design FOR the other 90%**[1]

**Design WITH the other 90%**[2]

GO **Design BY All**[3]


1. Smith, Cynthia E. *Design for the Other 90%*. New York: Smithsonian, Cooper-Hewitt, National Design Museum, 2007. Print.
2. Smith, Cynthia E. *Design with the Other 90%: Cities*. New York: Cooper-Hewitt National Design Museum, 2011. Print.
3. Musaazi, Moses Kizza, Abigail R. Mechtenberg, Juliet Nakibuule, Rachel Sensenig, Emmanuel Miyingo, John Vianney Makanda, Ali Hakimian, and Matthew J. Eckelman. "Quantification of Social Equity in Life Cycle Assessment for Increased Sustainable Production of Sanitary Products in Uganda." *Journal of Cleaner Production* (2013).

# Global Context + Energy E³ Pathway




**Energy E³ Pathway =**

**Energy Education + Engineering Design + Entrepreneurship**

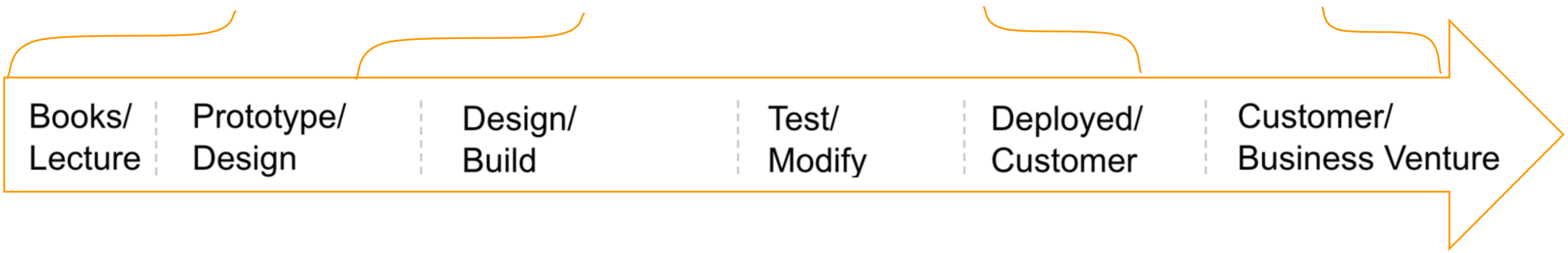
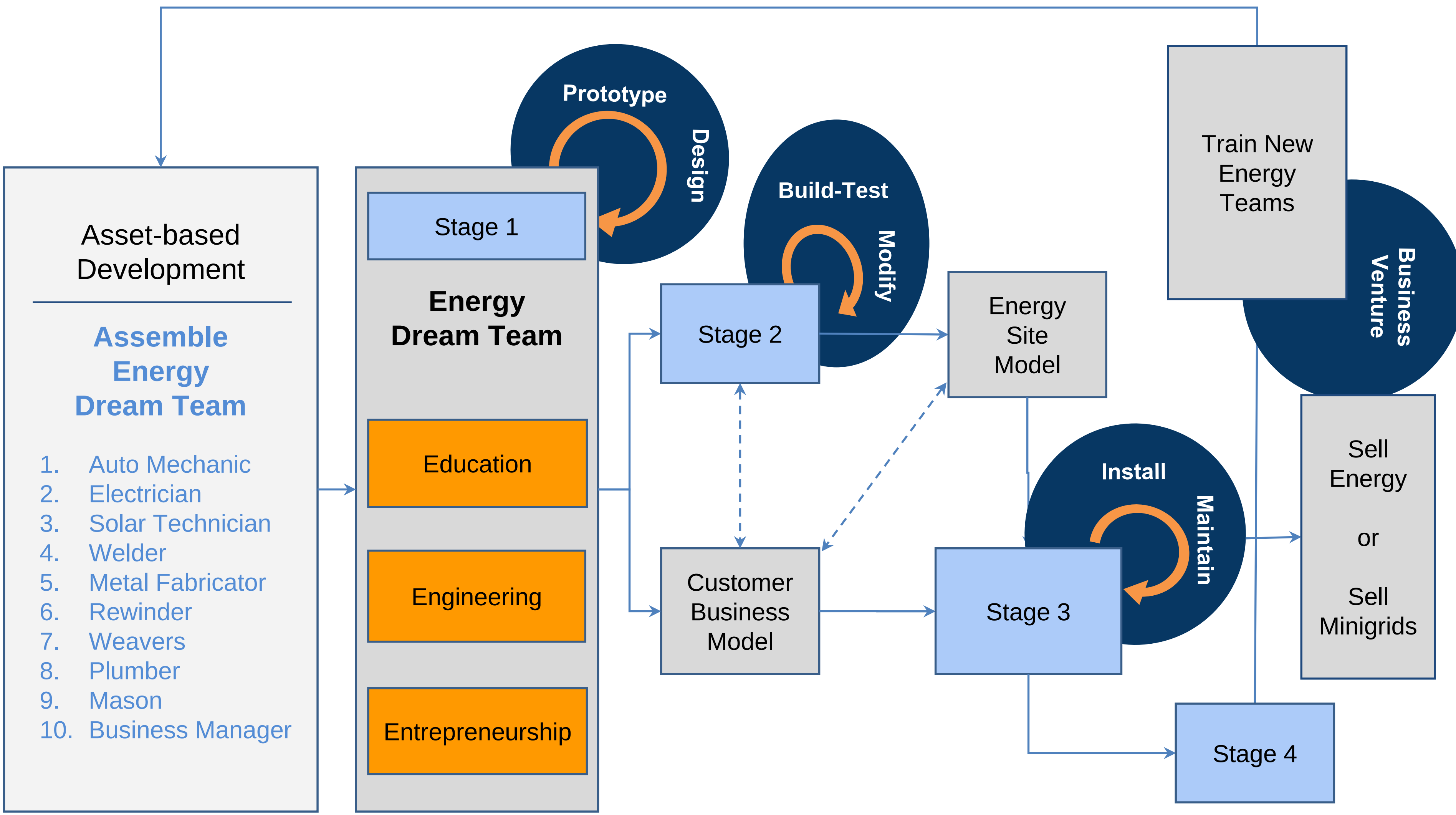



**Image Credit:**
Human Power as a Viable Electricity Gateway for Nations below 30 W / Capita. Mechtenberg, A.R, et al., Energy for Sustainable Development, 2010

# Energy $E^3$ Pathway In Action



# Energy $E^3$ Devices

## Mechanical to Electrical

Gravity Generator 1mW-5 W

Hand-crank Generator 50-250 W

Bicycle Generator 50-250 W

Merry-go-round Generator 100-750 W

VAWT Generator 1-50 kW

HAWT Generator 1-50 kW

Hydro Generator 1-50 kW

## Thermal to Electrical & Chemical to Thermal

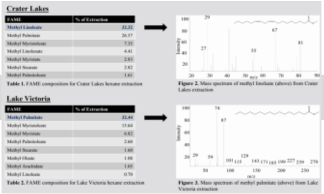
Thermal Electric Co-Gen Cookstove* 1-100 W

Waste Incinerator Generator* 1-50 kW

Concentrating Solar Power* 5-50 kW

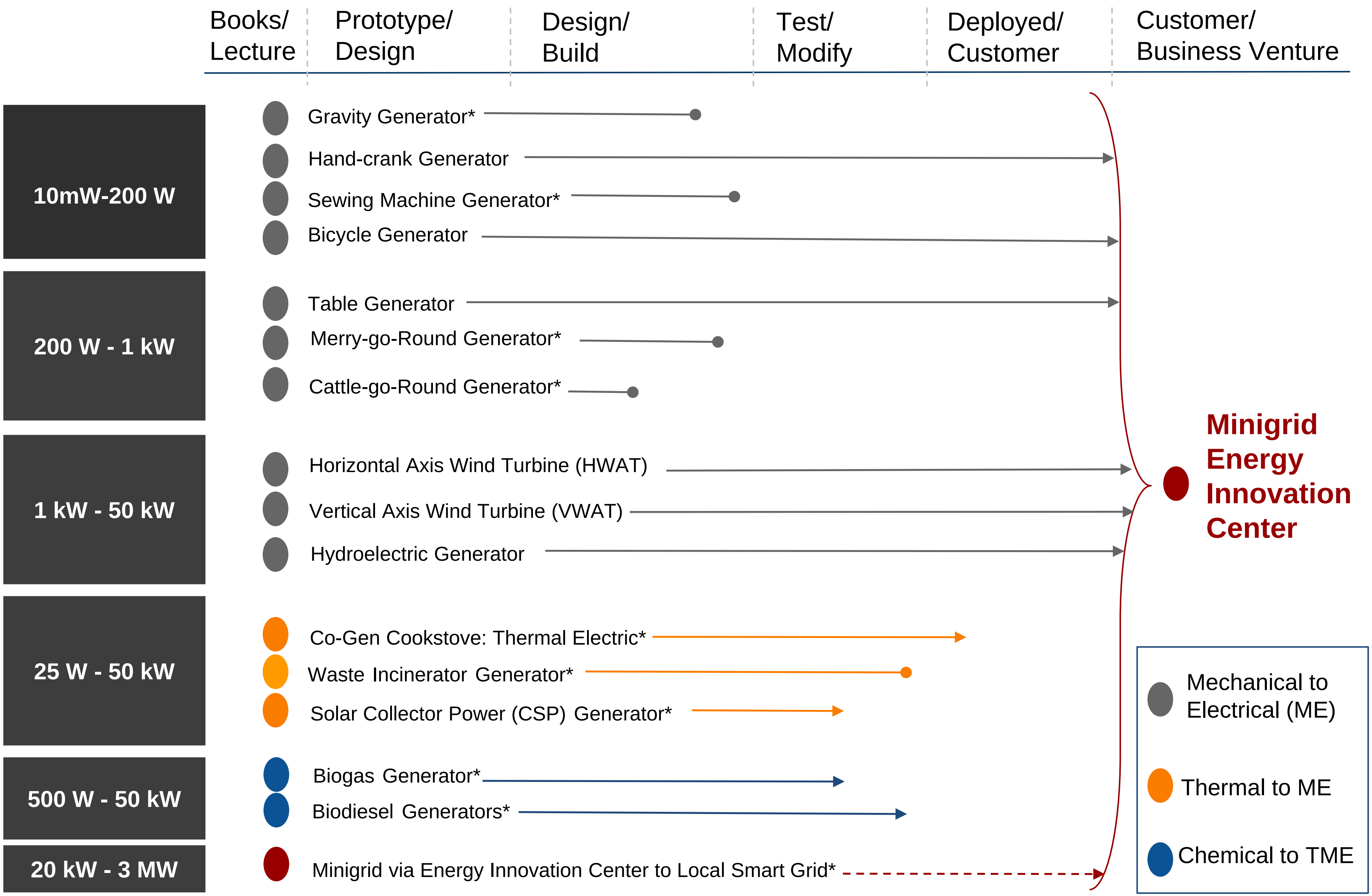
Biogas Cooking

Biogas to Petrol Generator* 5-50 kW



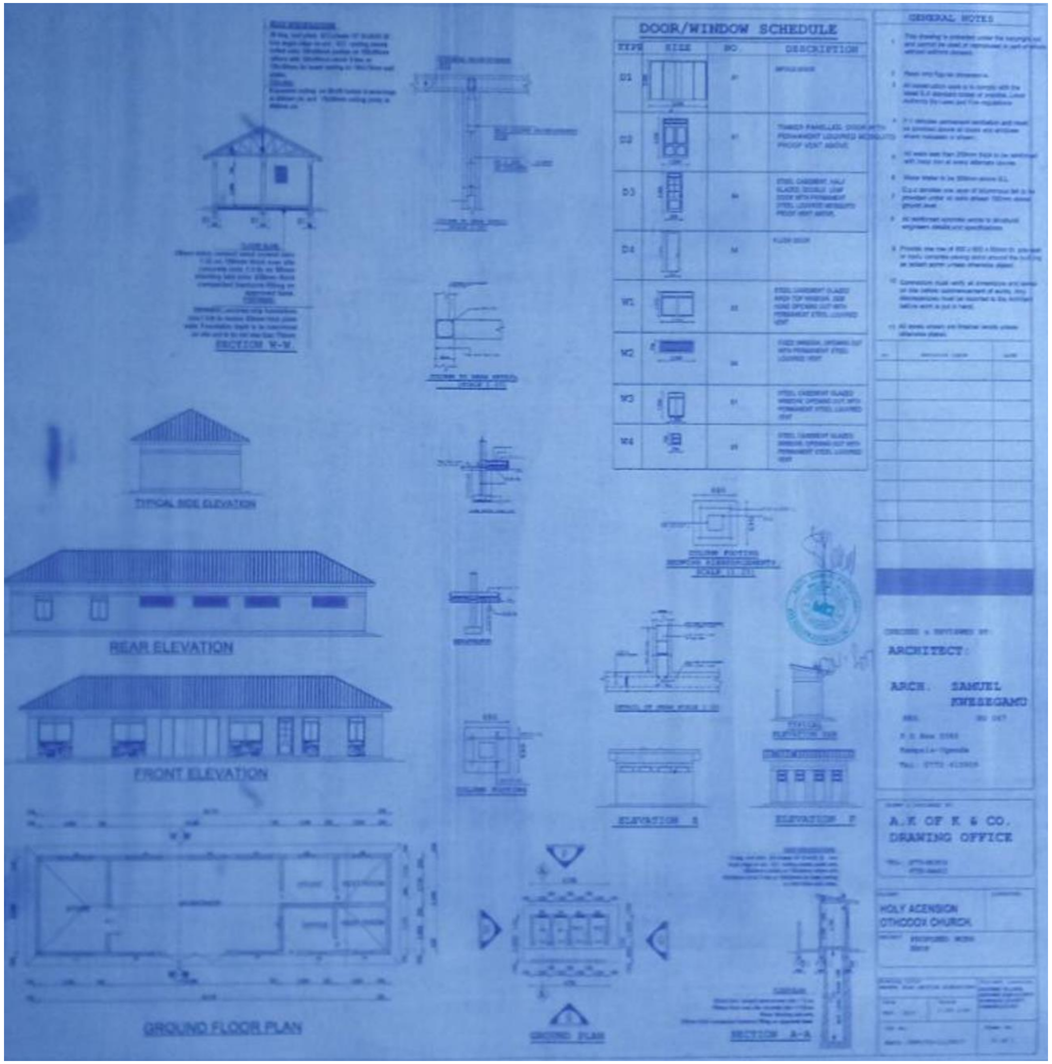

Algae into Biodiesel* 5-50 kW

# Education-Engineering-Entrepreneurship Pathway



# Energy $E^3$ Innovation Center

- Display $E^3$ Minigrid Devices
- Design/Build/Test/Modify/Control/Deploy Innovations
- Training Facility
- Educational Outreach Site
- Host Business Accelerator
- Host Trade Shows
- Attract Local Investors
- Propagate $E^3$ Innovations



Applied Energy Symposium:
**MIT A+B (AEAB2019)**

# A Cost Effective Way to Sustain 100% Reliability using Renewable Energy (RE) Complexity

A Mechtenberg[1,2*], Henri Francois[1], Brady McLaughlin[1], Robert A Stiller[1], A Stratman[1], L Omeeboh[1]

[1]Physics Department, University of Notre Dame

[2]ND Energy, University of Notre Dame

* Corresponding senior author/speaker

May 22-24, 2019 · MIT, Boston, USA
www.applied-energy.org/aeab2019

# Research Question

How can we **better** incorporate renewable energies into the grid?

Affordably → better ← Reliably

# Roadblocks

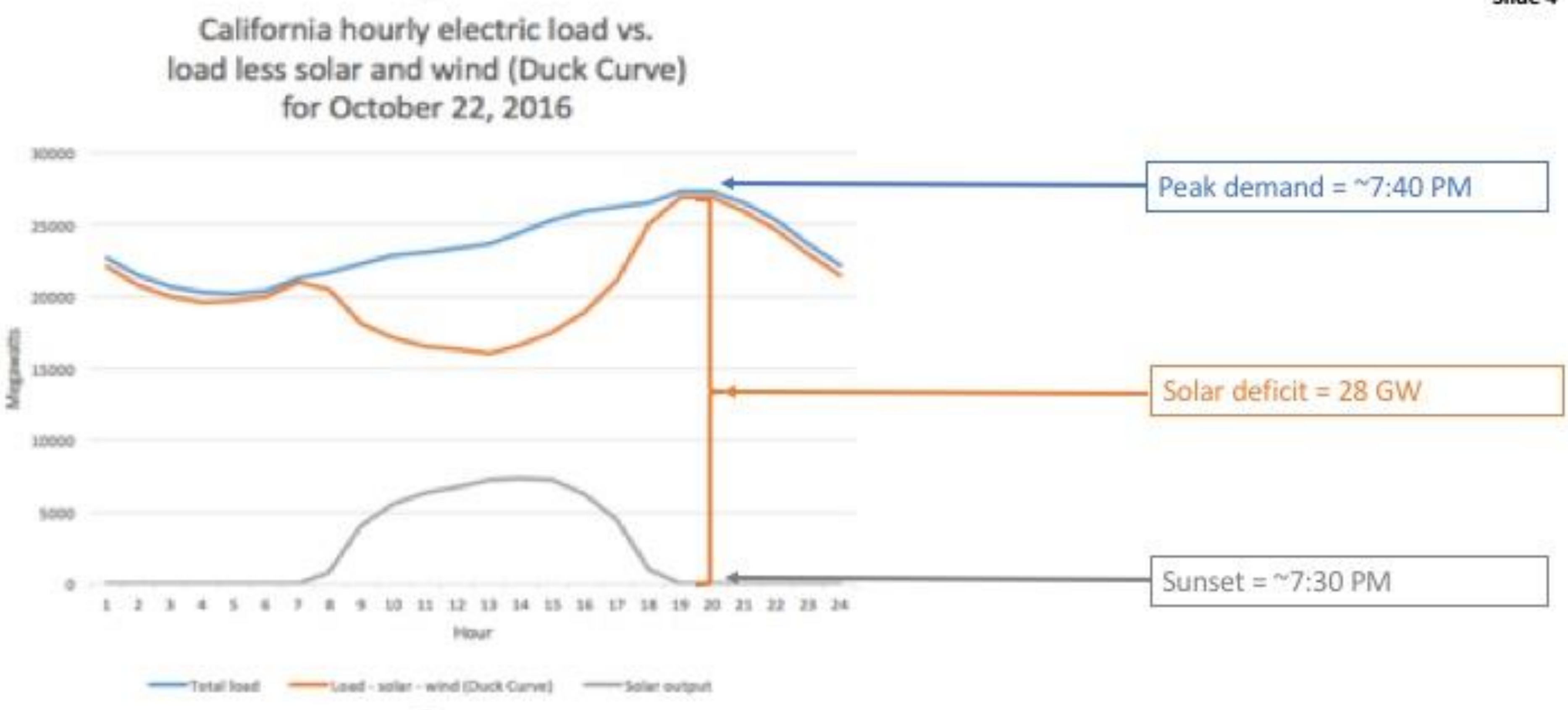
- US electricity is already cheap and reliable
- Status Quo with Solar, Wind, Batteries Adoption Slow

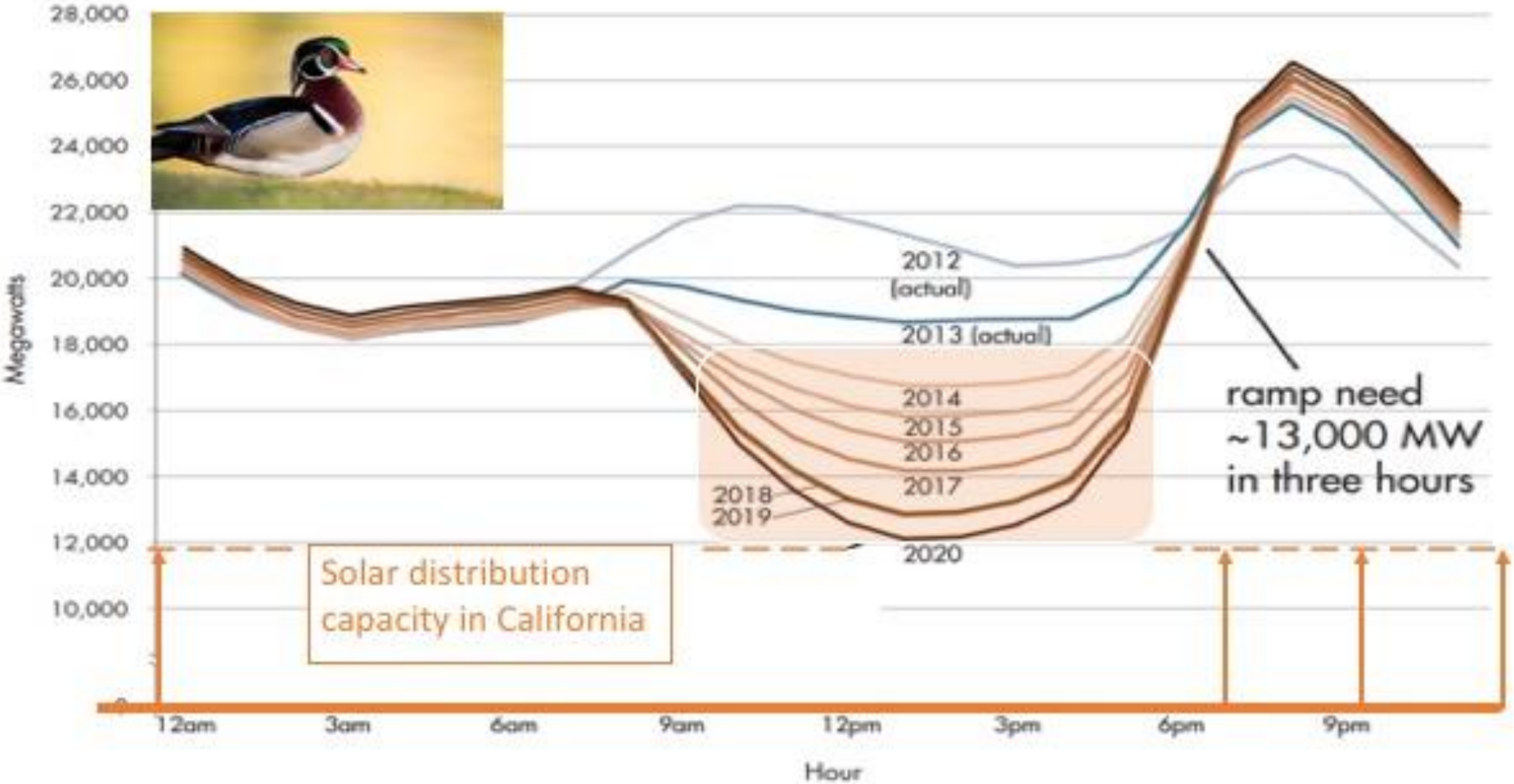
} Low incentive for change

WE MUST CHANGE ASAP

# Status Quo renewable energy incorporations are solving…

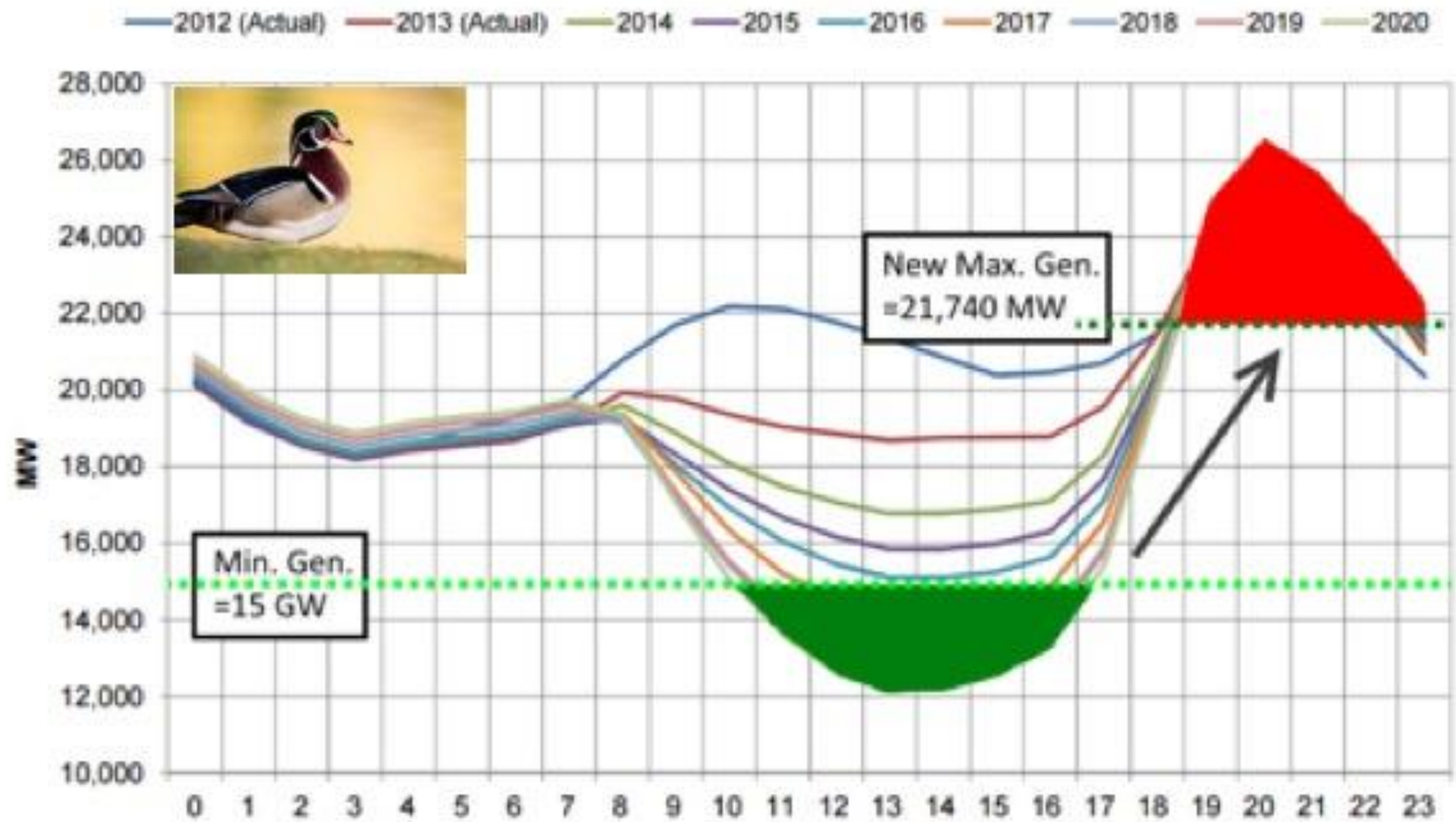
the duck curve,
for example.


California hourly electric load vs.
load less solar and wind (Duck Curve)
for October 22, 2016
30000
25000
20000
15000
10000
5000
0
Megawatts
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hour
Total load
Load - solar - wind (Duck Curve)
Solar output
Peak demand = ~7:40 PM
Solar deficit = 28 GW
Sunset = ~7:30 PM




Source: CAISO 2013

Source: Denholm, P., O'Connell, M., Brinkman, G. & Jorgenson, J. *Overgeneration from Solar Energy in California. A Field Guide to the Duck Chart.* (2015). doi:10.2172/1226167




Source: Energy Storage and the California "Duck Curve". Available at: http://large.stanford.edu/courses/2015/ph240/burnett2/ (Accessed: 25th February 2019)

# Status-Quo Solution



Use Storage with Solar and Wind

## New Solution

Overall Idea: We know there is order in chaos. Power systems are complex/chaotic, but potentially with usable chaotic order.

**How can types of chaotic order benefit design?**

Goal: Designed energy system solution incorporates the complexity as a benefit instead of a deficit.

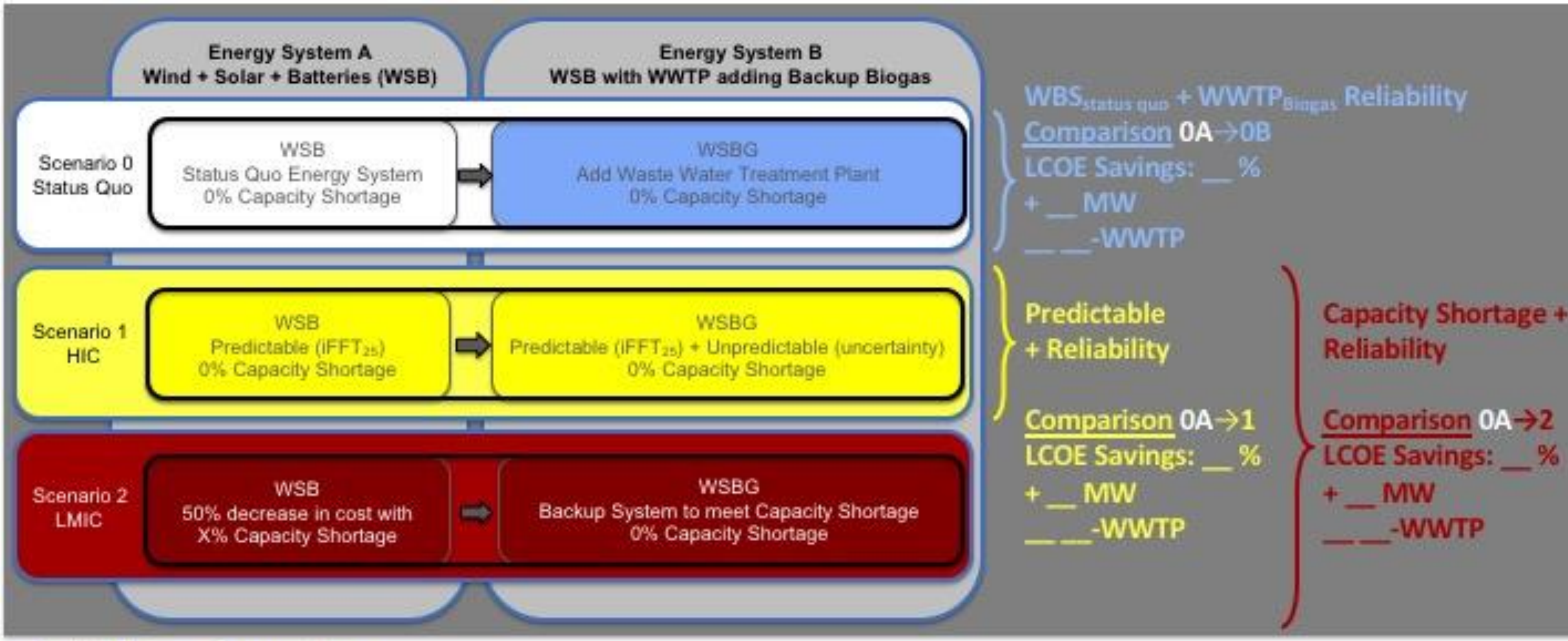
**How can chaotic order be found in this complexity?**

Novel Idea: Focus on HIC and LMIC Energy System Design Assumptions to understand chaotic order.

**Is using chaotic order in assumptions beneficial?**

Fractal by James Ahn

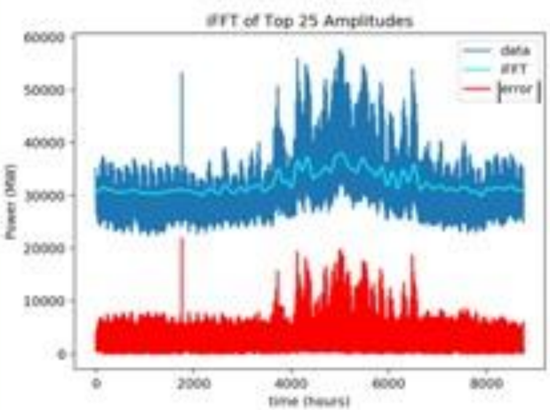
# Design Complexity for Affordability and Reliability



# FFT Analysis in Energy Systems
# City Power Load Example

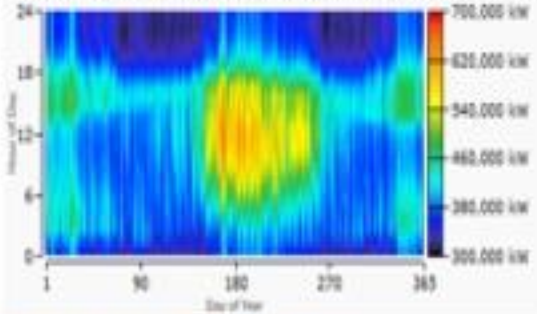
### Three Power versus Time Plots

1 Blue Data - Measured Data Utility
2 Cyan Data - Analyzed Predicted ($iFFT_{25}$)
3 Red Data – Calculated Uncertainty |error|



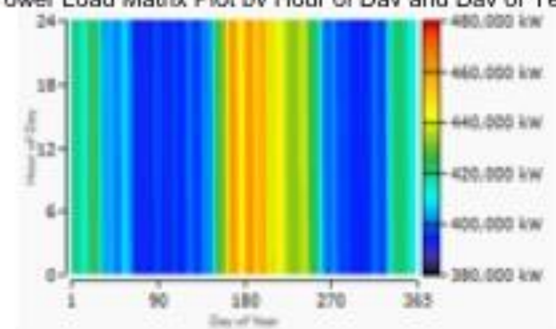

### Measured Utility DMAP

Power Load Matrix Plot by Hour of Day and Day of Year



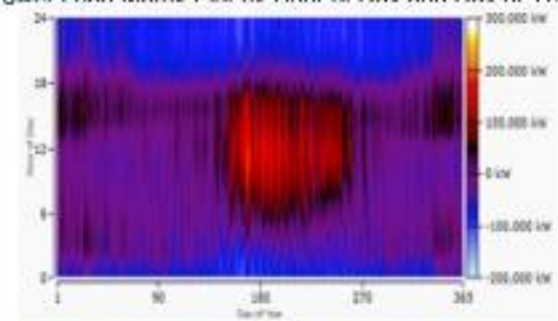

### Analyzed Utility $iFFT_{25}$ DMAP

Power Load Matrix Plot by Hour of Day and Day of Year



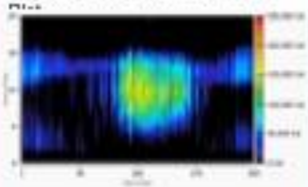

### Calculated Uncertainty DMAP

Power Load Matrix Plot by Hour of Day and Day of Year



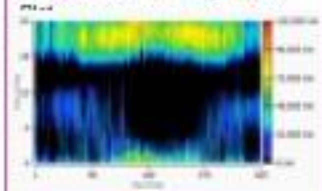

### Positive Uncertainty

Power Load Uncertainty Matrix Plot



### Negative Uncertainty

Power Load Uncertainty Matrix Plot



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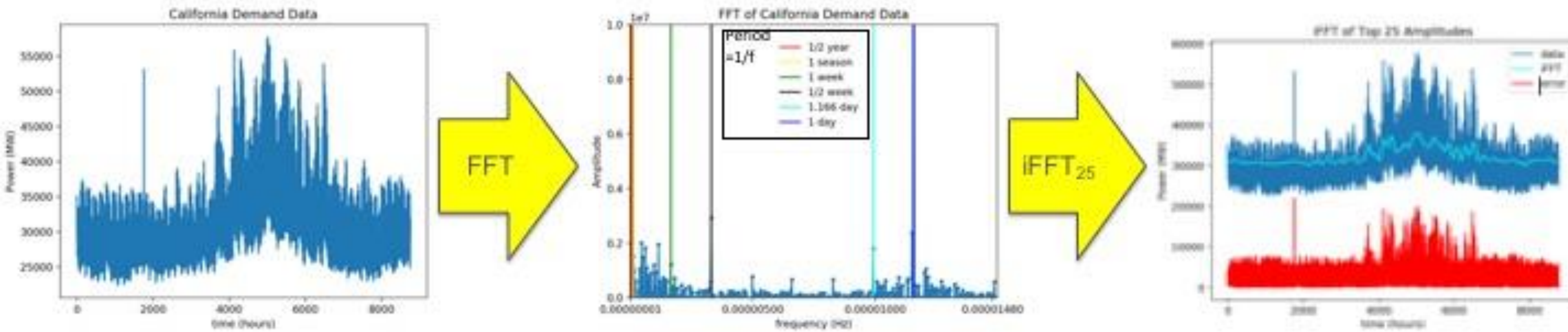
# Scenario 1

## Example FFT to $iFFT_{25}$ to Uncertainty

### Predictable & Unpredictable

### Example City Data, Analysis, and Calculation




Hour-by-Hour Real Data
EIA-Utility Grid of Region

Python FFT Analysis
Convert Frequency to Period
Take top 25 Amplitudes

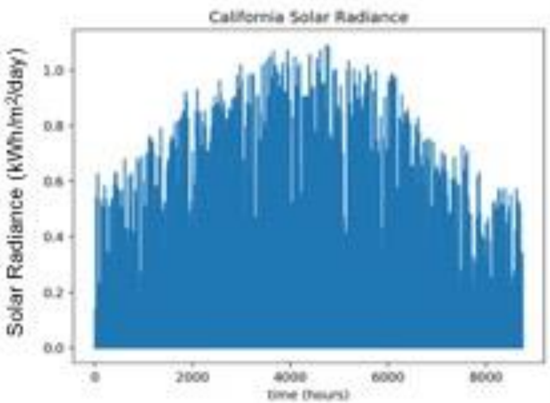
Python inverted FFT Analysis
Calculate Predicted Power Load
Calculate Unpredicted Power Load

# FFT Analysis in Energy Systems
# City Solar Radiance Example



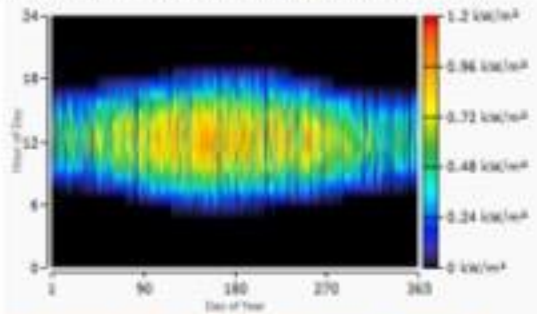
### Three Solar Radiance versus Time Plots

1 Blue Data - Measured Solar Radiance
2 Not shown here – Analyzed Predicted (iFFT$_{25}$)
3 Not shown here– Calculated Uncertainty |error|



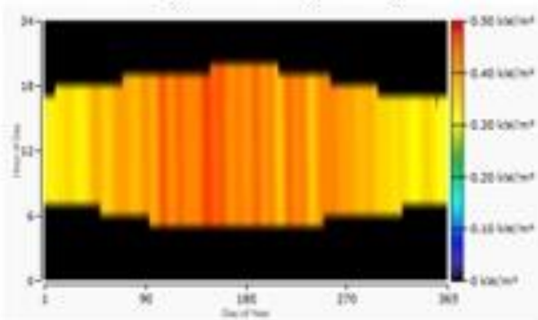

### Measured Solar Intensity DMAP

Solar Matrix Plot by Hour of Day and Day of Year



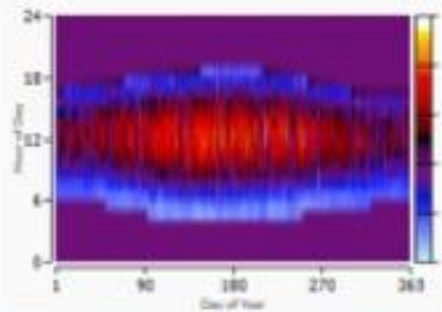

### Analyzed Solar Intensity iFFT$_{25}$ DMAP

Solar Matrix Plot by Hour of Day and Day of Year



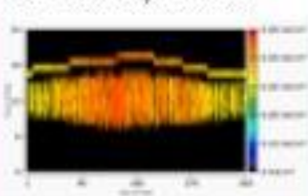

### Calculated Solar Intensity Uncertainty DMAP

Solar Matrix Plot by Hour of Day and Day of Year



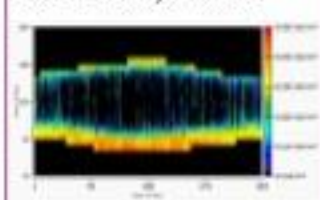

### Positive Uncertainty

Solar Uncertainty Matrix Plot



### Negative Uncertainty

Solar Uncertainty Matrix Plot

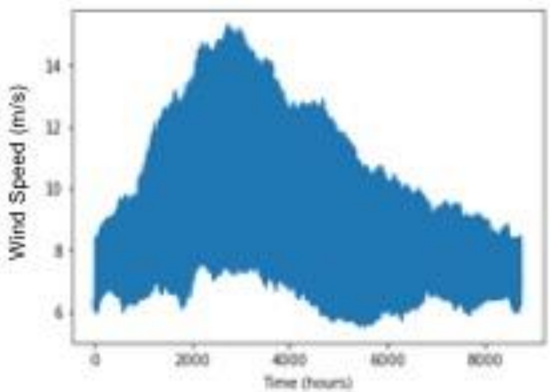


# FFT Analysis in Energy Systems
# City Wind Speed Example



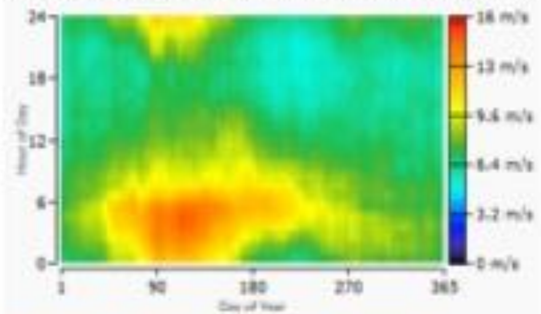
### Three Wind Speed versus Time Plots

1 Blue Data - Measured Wind Speed
2 Not shown here – Analyzed Predicted ($iFFT_{25}$)
3 Not shown here– Calculated Uncertainty |error|



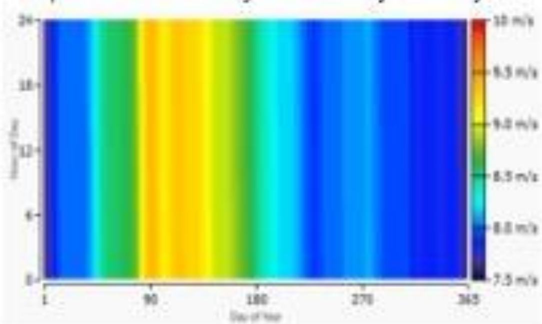

### Measured Wind Speed DMAP

Wind Speed Matrix Plot by Hour of Day and Day of Year



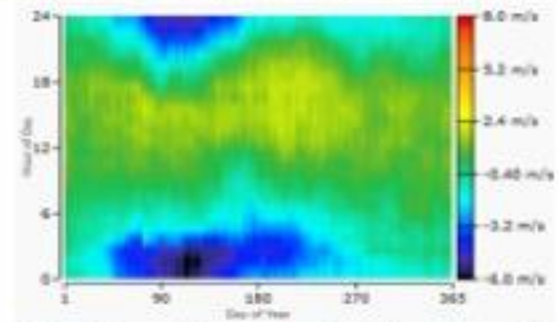

### Analyzed Wind Speed $iFFT_{25}$ DMAP

Wind Speed Matrix Plot by Hour of Day and Day of Year



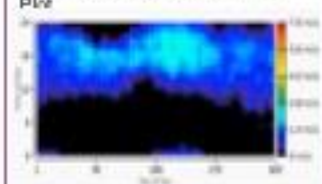

### Calculated Wind Speed Uncertainty DMAP

Wind Speed Matrix Plot by Hour of Day and Day of Year



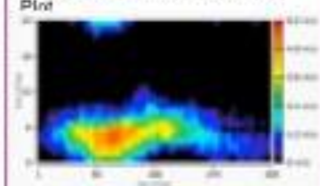

### Positive Uncertainty

Wind Speed Uncertainty Matrix Plot



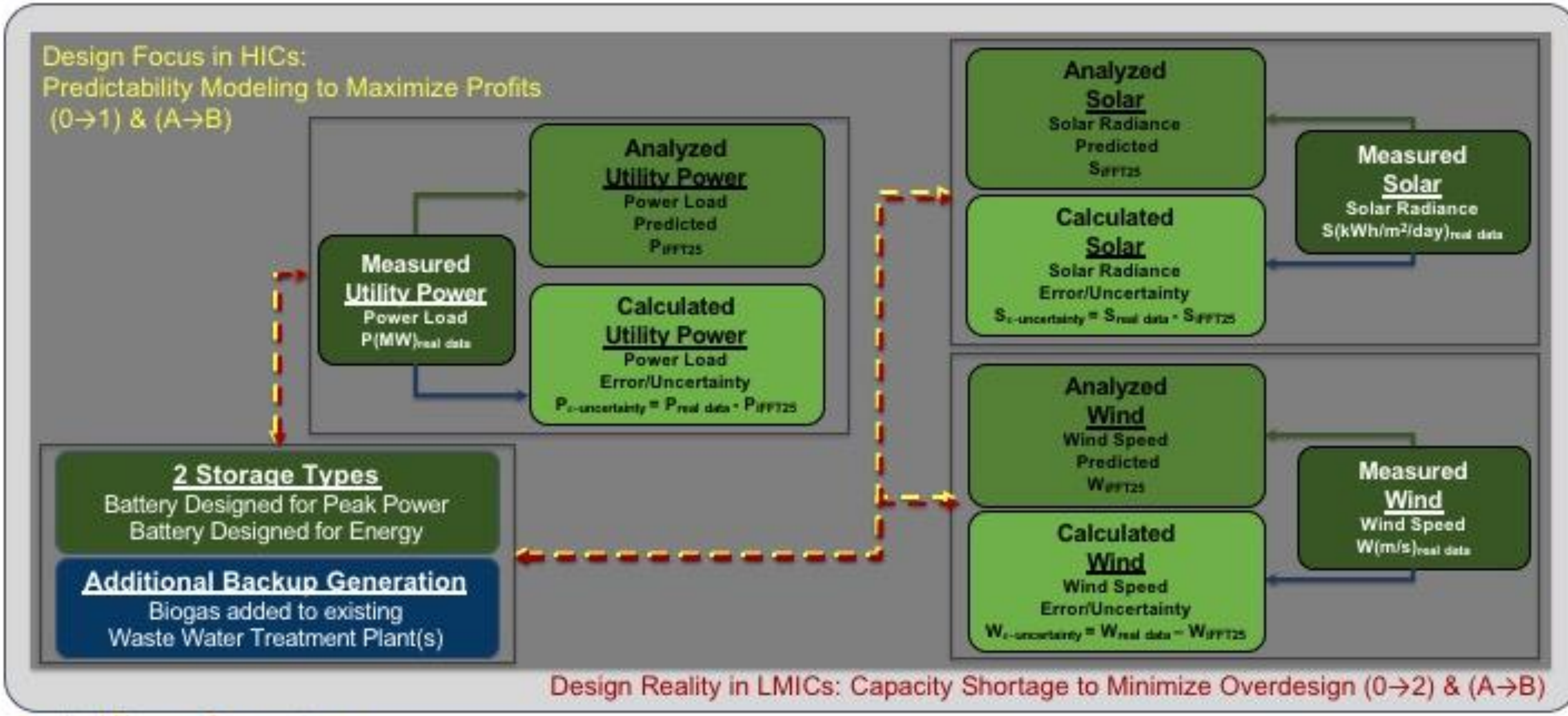
### Negative Uncertainty

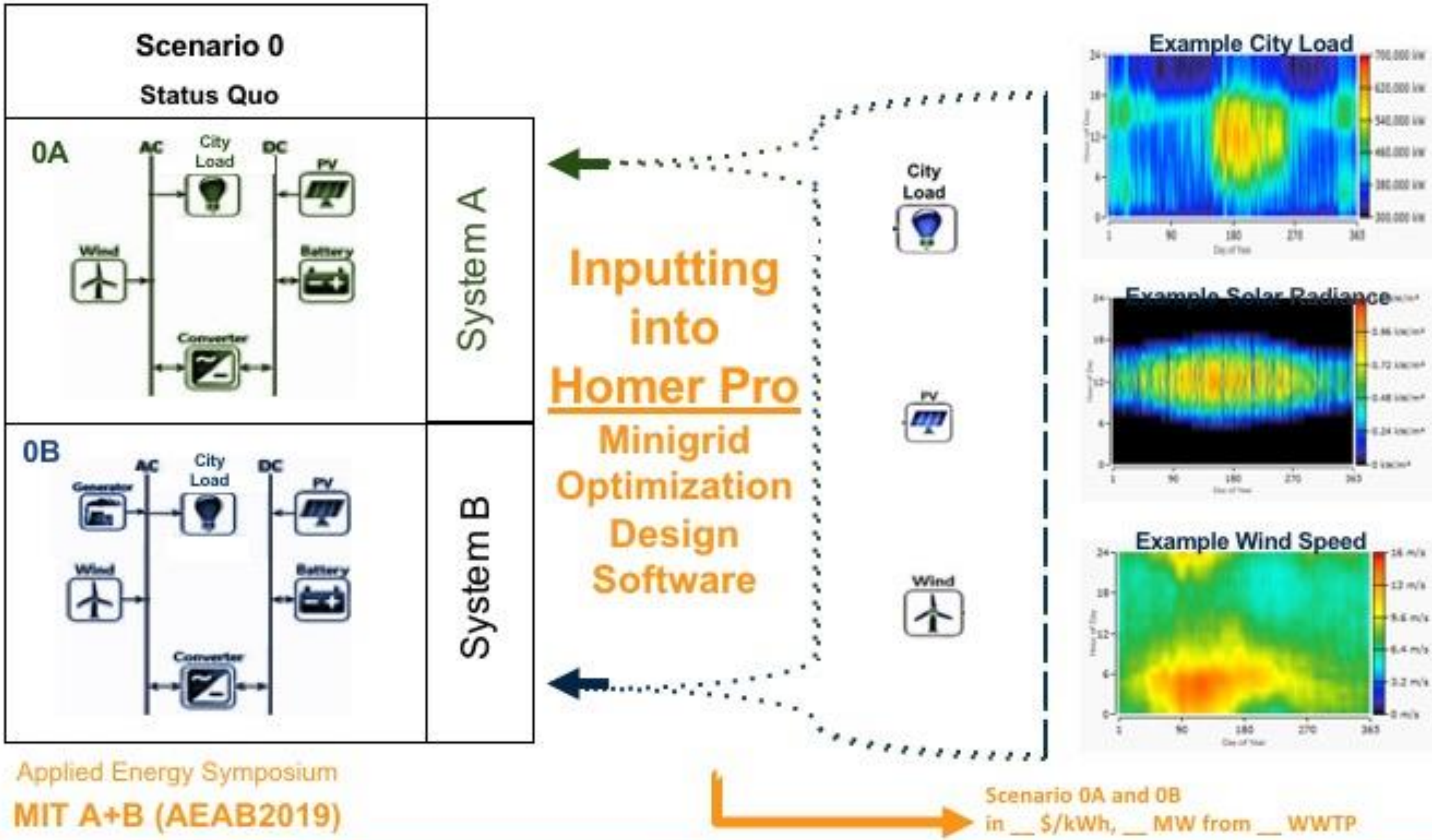
Wind Speed Uncertainty Matrix Plot



# Flow Chart for Energy Scenario (0-1-2) & System (A+B) Designs





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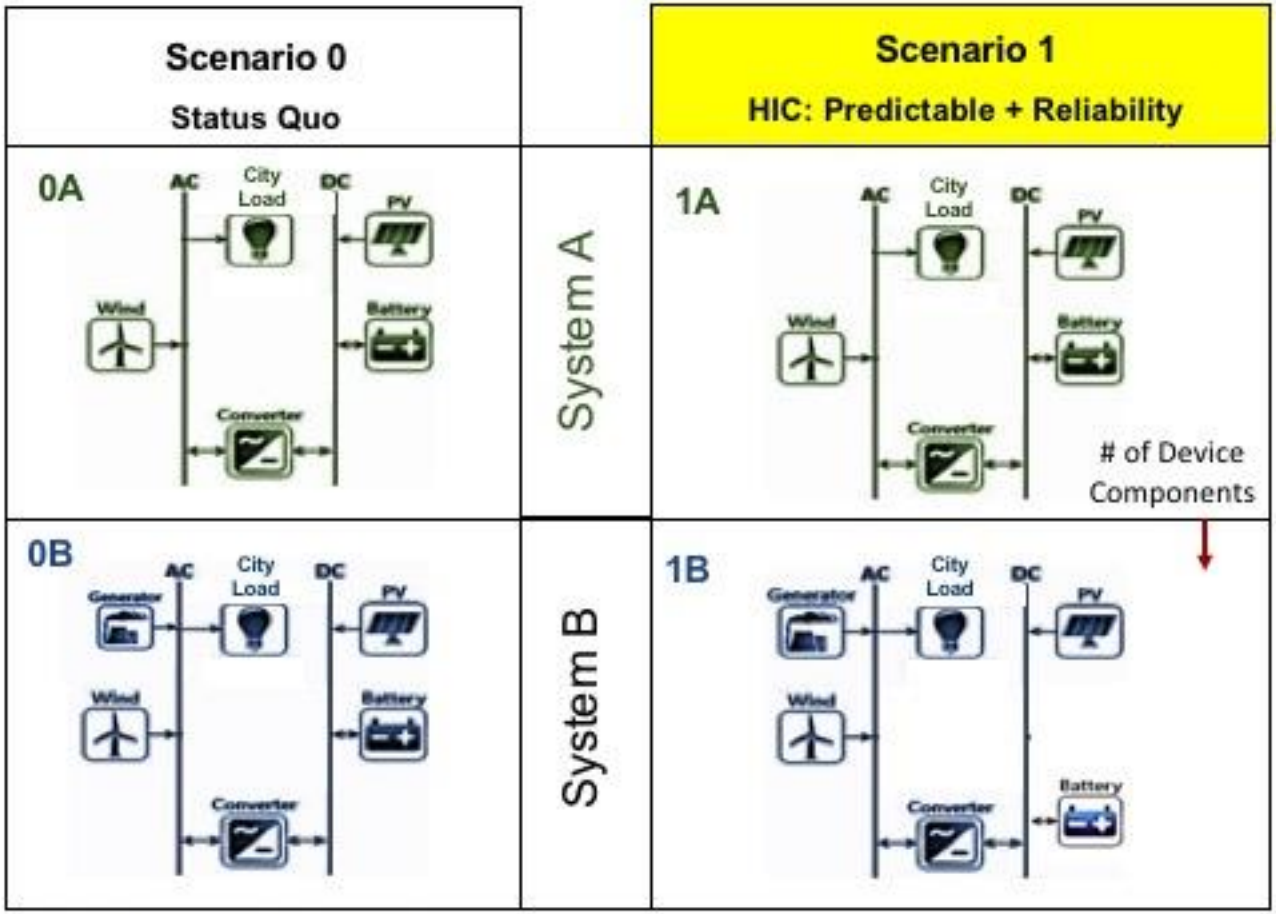
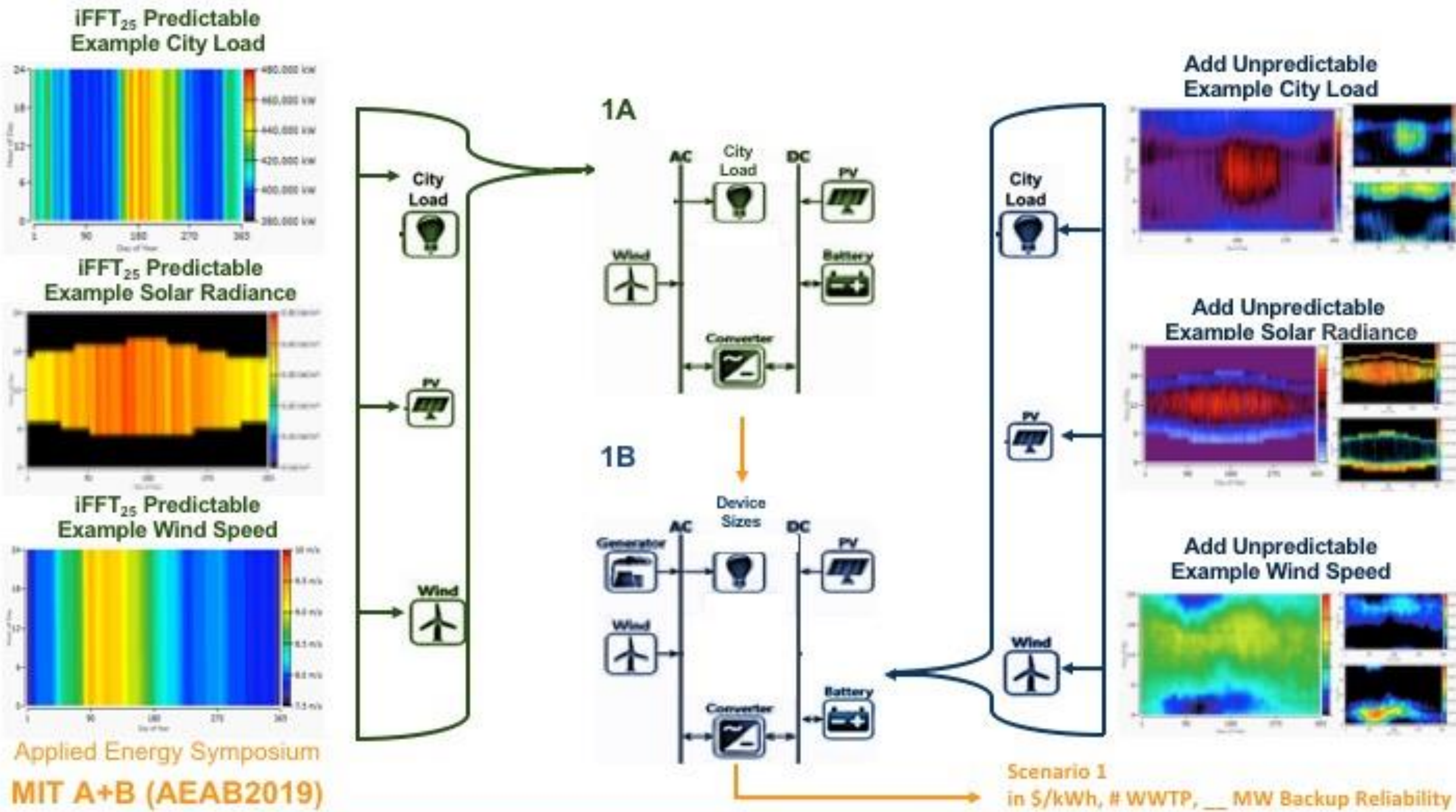
Lambert, T. , Gilman, P. and Lilienthal, P. (2006). Micropower System Modeling with Homer. In Integration of Alternative Sources of Energy (eds F. A. Farret and M. G. Simões). doi:10.1002/0471755621.ch15

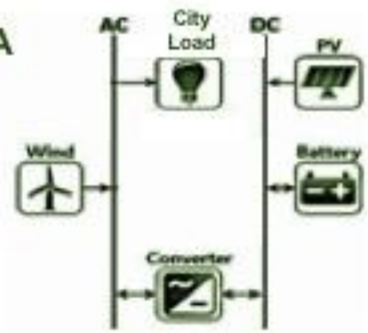

Scenario 0
Status Quo
Scenario 1
HIC: Predictable + Reliability
0A
1A
0B
1B
System A
System B
AC
DC
City Load
PV
Wind
Battery
Converter
Generator
# of Device Components



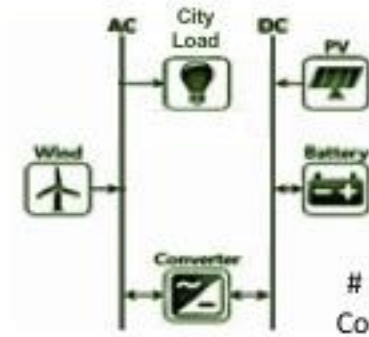
iFFT25 Predictable Example City Load
iFFT25 Predictable Example Solar Radiance
iFFT25 Predictable Example Wind Speed
City Load
PV
Wind
1A
AC
DC
City Load
PV
Wind
Battery
Converter
1B
Device Sizes
AC
DC
Generator
PV
Wind
Battery
Converter
City Load
PV
Wind
Add Unpredictable Example City Load
Add Unpredictable Example Solar Radiance
Add Unpredictable Example Wind Speed
Scenario 1
in $/kWh, # WWTP, __ MW Backup Reliability
Applied Energy Symposium
MIT A+B (AEAB2019)

| Scenario 0<br>Status Quo | | Scenario 1<br>HIC: Predictable + Reliability | Scenario 2<br>LMIC: Capacity Shortage + Reliability |
|---|---|---|---|
| 0A | System A | 1A | 2A |
| 0B | System B | 1B | 2B |

**0A**

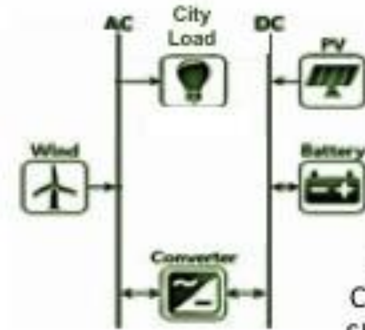



**1A**




# of Device Components

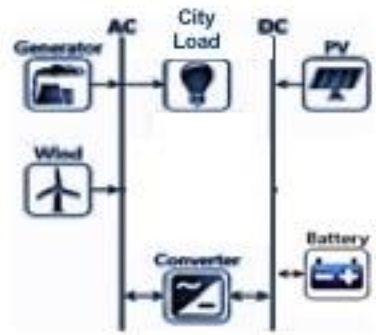
**2A**



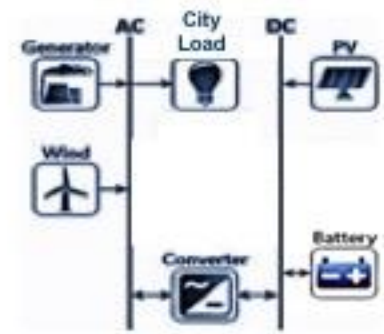

X % Capacity Shortage

**0B**


**1B**

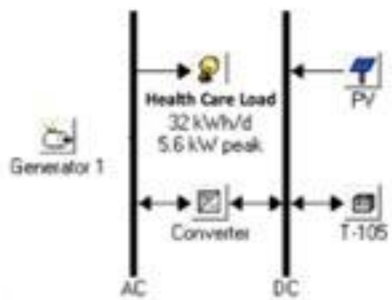



**2B**



# LMIC Reality for Health Care Electricity Systems

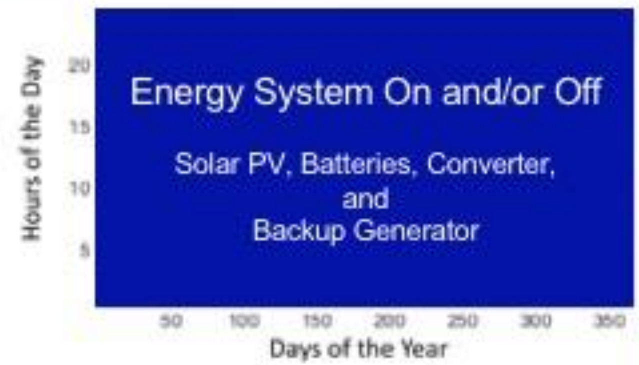
Source: Ali Al-Karaghouli, L.L. Kazmerski, Optimization and life-cycle cost of health clinic PV system for a rural area in southern Iraq using HOMER software, Solar Energy, Volume 84, Issue 4, 2010, Pages 710-714, ISSN 0038-092X.

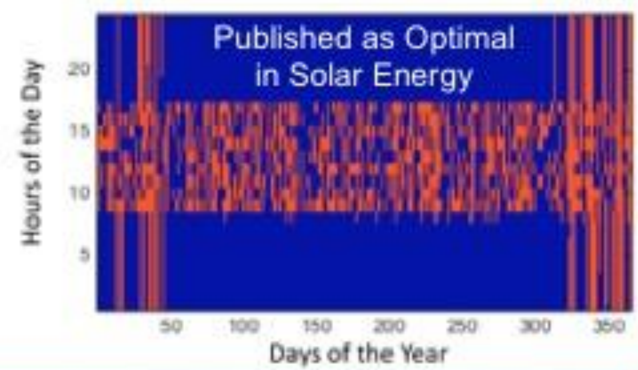



| | Iraq - *Solar Energy*, 2010 |
|---|---|
| Cost of Electricity ($/kWh) | $0.26/kWh |
| Energy Capacity Shortage (%) $\frac{E_{not\ served}}{E_{load}}$ | 18 % |
| Time Capacity Shortage (%) $\frac{t_{not\ served}}{t_{load}}$ | 25 % |
| Failures (hrs/year) | 2160 hours |
| Back-up System | Install Solar no backup chosen |

*On*

*Off*

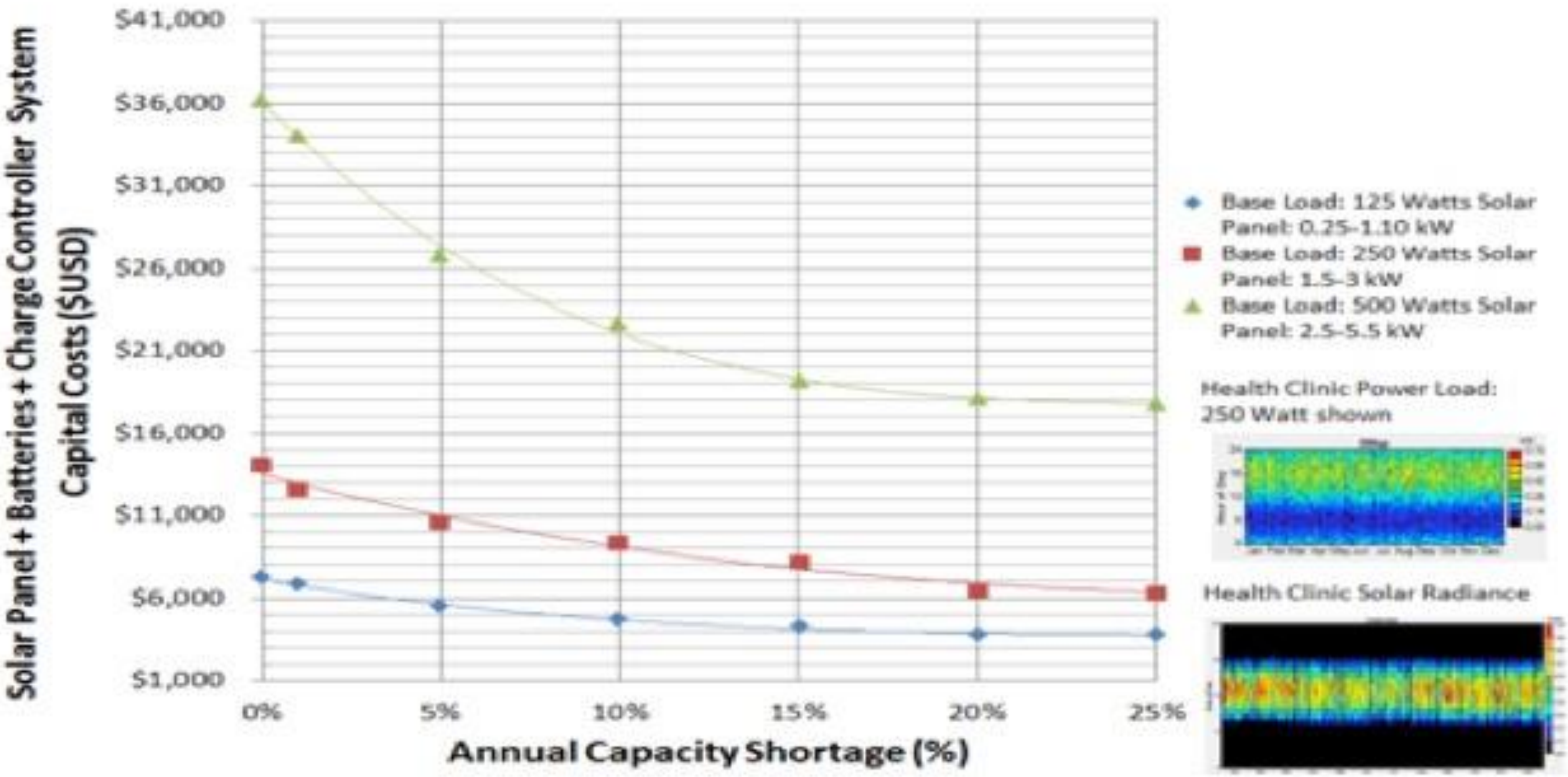



A Mechtenberg, B McLaughlin, M DiGaetano, A Awodele, M Musaazi, L Nanjula, M Shrime. Impact of electricity failures on health care in terms of hidden costs and risks: A value of statistical life lost divided by energy shortage model events into VSLE risk chart. PMEDICINE-D-19-01106 [underreview Apr 1, 2019]

# LMIC - Electricity and Health Care Trade-off





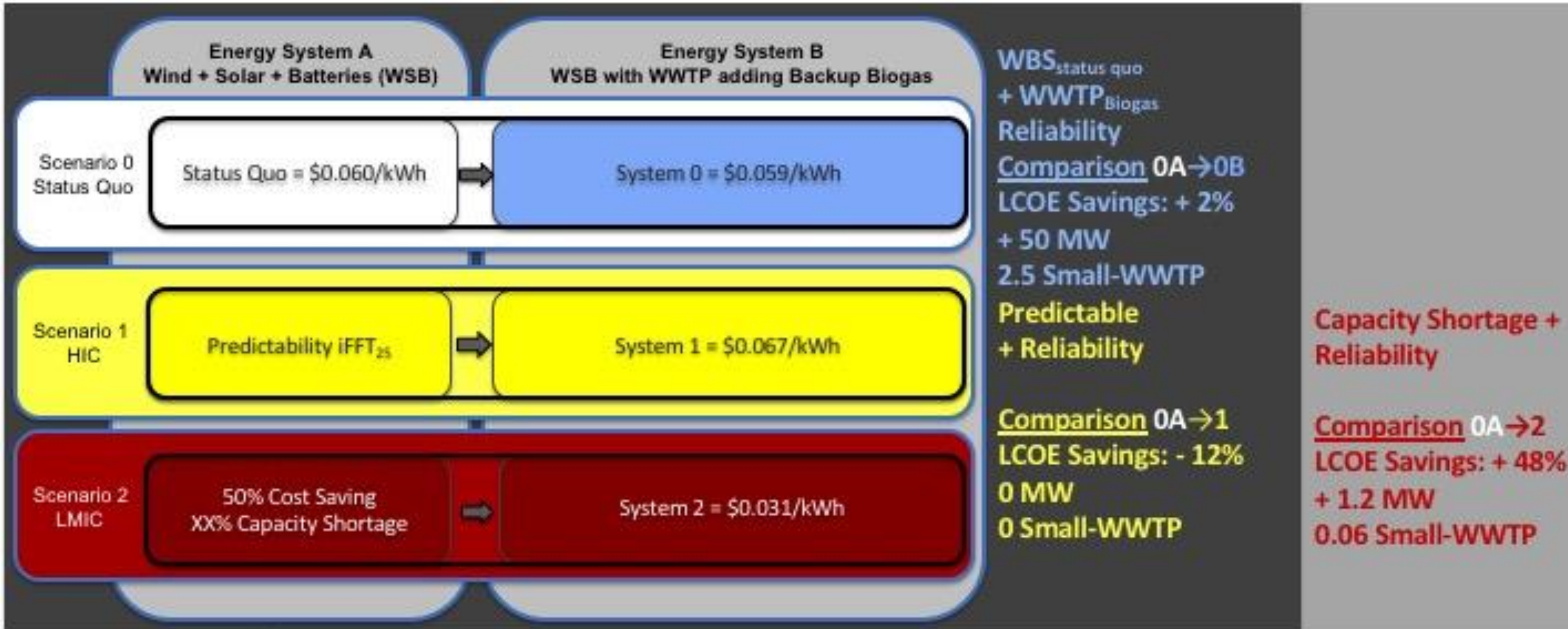

Cost savings of 50% with Reliability for Solar Panels at 80% (called Capacity Shortage).
Back-Up Systems needed only for 20% of the time (life-and-death situations).

Source: Mechtenberg, A.R., Musaazi, M.E., Senabulya, N., & Makanda, J. (2012). Socio-technical implication of renewable energy sources: African health care case study with Monte-Carlo simulations. *2012 IEEE International Symposium on Sustainable Systems and Technology (ISSST)*, 1-6.

# Boise, ID, US



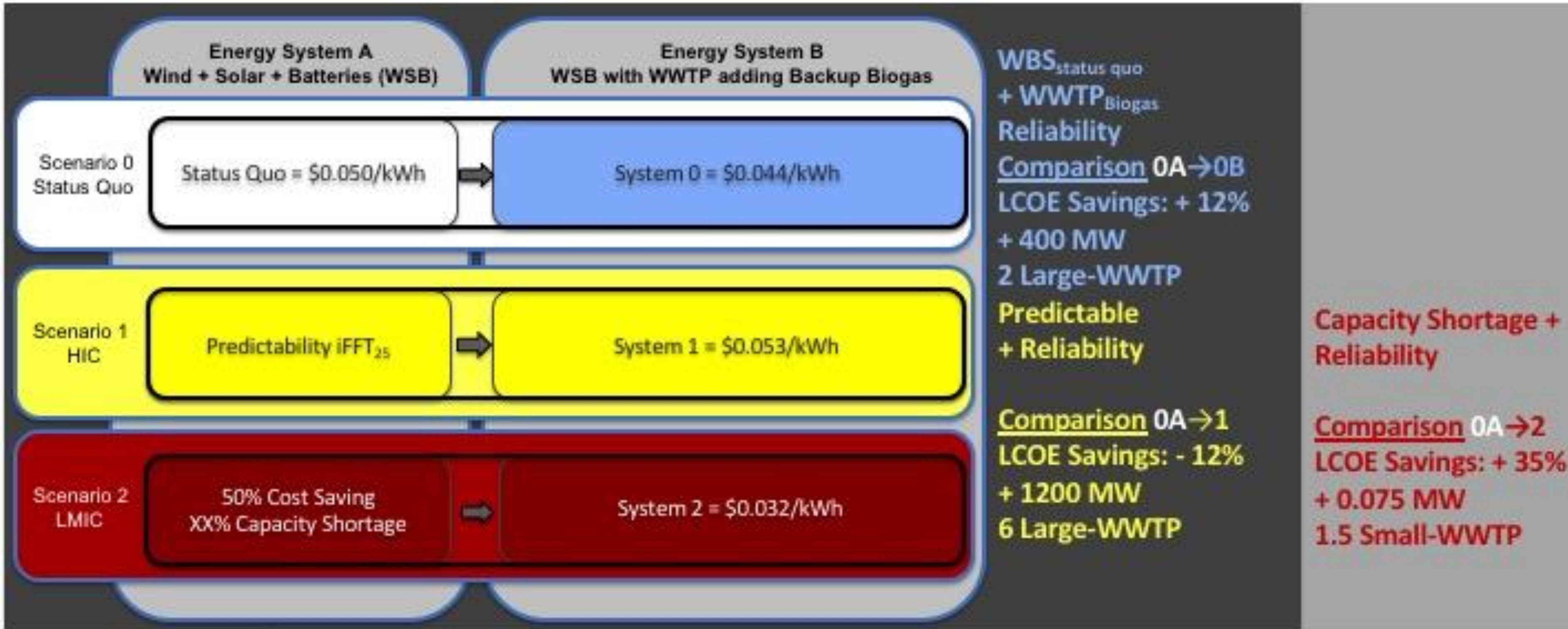
City Example Result



# Charlotte, NC, US



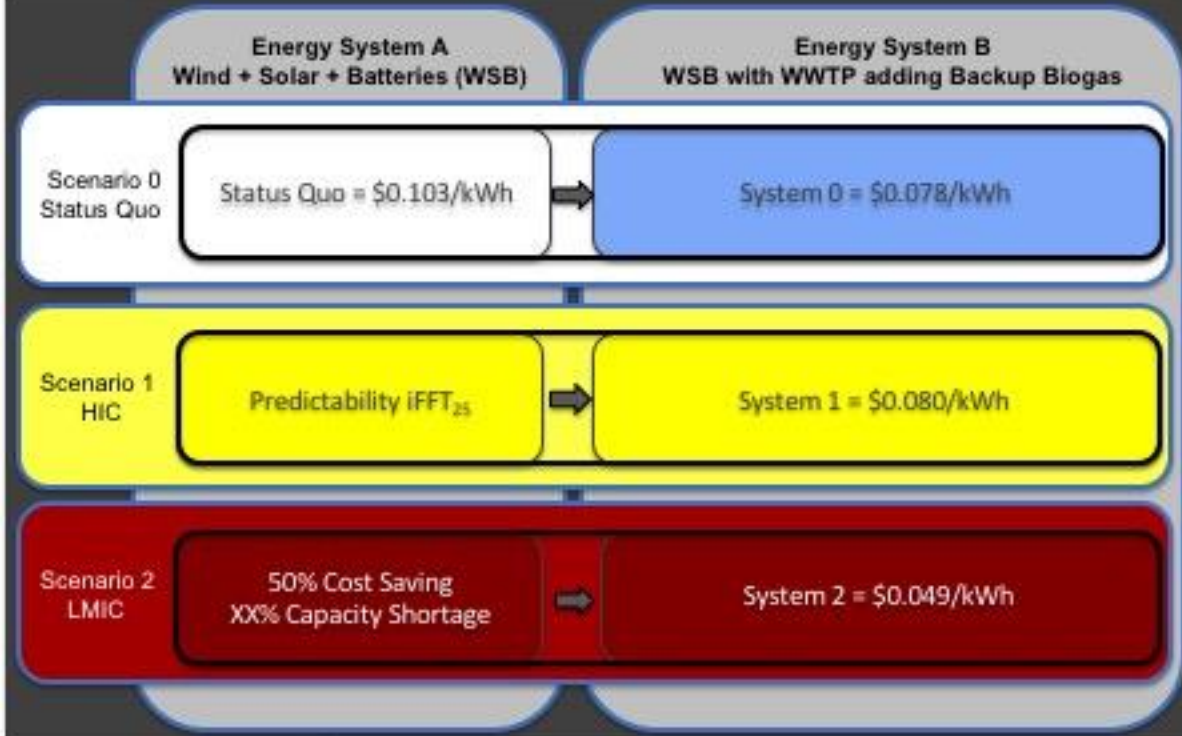
City Example Result



# Nashville, TN, US

City Example Result






$WBS_{status\ quo}$
$+ WWTP_{Biogas}$
Reliability
Comparison 0A→0B
LCOE Savings: + 24%
+ 600 MW
3 Large-WWTP

Predictable
+ Reliability

Comparison 0A→1
LCOE Savings: + 22%
+ 400 MW
2 Large-WWTP

Capacity Shortage +
Reliability

Comparison 0A→2
LCOE Savings: + 52%
+ 0.075 MW
1.5 Small-WWTP

# Scenario and Energy System Results

For 100+ US Cities (10+ million data points)

Not most recent result as undergraduate student made a mistake that I am now correcting (really need API to work).

| Scenarios (0-1-2) and Energy Systems (A+B) | Number of Cities where Model is Lowest Levelized Cost of Electricity Optimization Technique Matters ($/kWh) |
|---|---|
| Status-quo WSB: 0A | 4.5% |
| WSB + Adding Biogas$_{WWTP}$: 0B | 9.1 % |
| HIC Assumptions: 1 | 27% |
| LMIC Assumptions: 2 | 59 % |

# Research Question with Results

How can we **better** incorporate renewable energies (RE) into the grid?

Affordably

Reliably

20% to 50%
Costs Savings
Affordability

0 to 6 L-WWTP
Backup Biogas
Reliability

Using complexity of renewable energy as a benefit and not as a deficit…

**Design with RE Complexity**

for increase in likelihood to mitigate and adapt to climate change.

Applied Energy Symposium:
**MIT A+B (AEAB2019)**

# A Cost Effective Way to Sustain 100% Reliability using Renewable Energy (RE) Complexity

A Mechtenberg[1,2*], Henri Francois[1], Brady McLaughlin[1], Robert A Stiller[1], A Stratman[1], L Omeeboh[1]

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ND Energy

* Corresponding senior author/speaker

icae

May 22-24, 2019 · MIT, Boston, USA
www.applied-energy.org/aeab2019

# Homer Pro Economic Inputs

| **Input** | **Capital** | **Replacement** | **O&M** | **Key Reference** |
|---|---|---|---|---|
| Solar Panel | $3,000/kW | $3,000/kW<br>(Lifetime 15 years) | Homer Pro Economic Input | Dr. Peter Fox-Penner. *Smart Power: Climate Change, the Smart Grid, & the Future of Electric Utilities*. (Island Press, 2014). |
| Converter<br>(Charge Controller) | $300/kW<br>(95% efficiency) | $300/kW<br>(Lifetime 15 years) | Homer Pro Economic Input | Dr. Peter Fox-Penner. *Smart Power: Climate Change, the Smart Grid, & the Future of Electric Utilities*. (Island Press, 2014). |
| Battery | $700,000/Battery<br>(1 MWh, 600V)<br>($700/kWh) | $700,000<br>(Lifetime 15 years) | Homer Pro Economic Input | Energy Information Administration. U.S. Battery Storage Market Trends. 32 (2018). |
| Wind Turbine | $2,700,000/1.5 MW<br>($2,700/kW) | $2,500,000/1.5 MW<br>(Lifetime 20 years) | $30,000/year | Wilson, M. Lazard's Levelized Cost of Electricity Analysis—Version 4.0. 60 |
| Biogas Generator | $2,500,000/400 MW | $1,800,000/400 MW<br>(Lifetime 20,000 hrs) | $0.03/operational hour | Environmental Protection Agency. Opportunities for Combined Heat and Power at Wastewater Treatment Facilities: Market Analysis and Lessons from the Field. *Proceedings of the Water Environment Federation* **2012**, 4532–4588 (2012). |

# Biogas Generators added to WWTP

Table 14: Estimated Cost to Generate Anaerobic Digester Gas Electricity (Case 3 – CHP Heat Displaces Natural Gas for Both Digester and Space Heating)

| Climate Zone | WWTP Plant Size (MGD) | Corresponding CHP System Size (kW) | Estimated Net Cost to Generate ($/kWh) | | | | |
|---|---|---|---|---|---|---|---|
| | | | Micro-turbine | Rich-Burn Engine | Fuel Cell | Lean-Burn Engine | Turbine |
| 1 – Cold | 1–5 | 30–130 | 0.043 | 0.044 | — | — | — |
| | 5–10 | 130–260 | 0.043 | 0.035 | 0.068 | — | — |
| | 10–20 | 260–520 | 0.043 | 0.035 | 0.068 | 0.029 | — |
| | 20–40 | 520–1,040 | — | — | 0.068 | 0.029 | — |
| | 40–150 | 1,040–3,900 | — | — | 0.068 | 0.022 | — |
| | >150 | >3,900 | — | — | — | 0.022 | 0.011 |
| 2 – Cold/Moderate | 1–5 | 30–130 | 0.043 | 0.047 | — | — | — |
| | 5–10 | 130–260 | 0.043 | 0.037 | 0.068 | — | — |
| | 10–20 | 260–520 | 0.043 | 0.037 | 0.068 | 0.029 | — |
| | 20–40 | 520 - 1,040 | — | — | 0.068 | 0.029 | — |
| | 40–150 | 1,040–3,900 | — | — | 0.068 | 0.022 | — |
| | >150 | >3,900 | — | — | — | 0.022 | 0.011 |
| 3 – Moderate/Mixed | 1–5 | 30–130 | 0.043 | 0.050 | — | — | — |
| | 5–10 | 130 - 260 | 0.043 | 0.039 | 0.068 | — | — |
| | 10–20 | 260–520 | 0.043 | 0.039 | 0.068 | 0.030 | — |
| | 20–40 | 520–1,040 | — | — | 0.068 | 0.030 | — |
| | 40–150 | 1,040–3,900 | — | — | 0.068 | 0.022 | — |
| | >150 | >3,900 | — | — | — | 0.022 | 0.012 |
| 4 – Warm/Hot | 1–5 | 30–130 | 0.043 | 0.052 | — | — | — |
| | 5–10 | 130–260 | 0.043 | 0.040 | 0.068 | — | — |
| | 10–20 | 260–520 | 0.043 | 0.040 | 0.068 | 0.033 | — |
| | 20–40 | 520–1,040 | — | — | 0.068 | 0.033 | — |
| | 40–150 | 1,040–3,900 | — | — | 0.068 | 0.022 | — |
| | >150 | >3,900 | — | — | — | 0.022 | 0.014 |
| 5 – Hot | 1–5 | 30–130 | 0.045 | 0.053 | — | — | — |
| | 5–10 | 130–260 | 0.045 | 0.042 | 0.068 | — | — |
| | 10–20 | 260–520 | 0.045 | 0.042 | 0.068 | 0.034 | — |
| | 20–40 | 520–1,040 | — | — | 0.068 | 0.034 | — |
| | 40–150 | 1,040–3,900 | — | — | 0.068 | 0.024 | — |
| | >150 | >3,900 | — | — | — | 0.024 | 0.016 |

Environmental Protection Agency. Opportunities for Combined Heat and Power at Wastewater Treatment Facilities: Market Analysis and Lessons from the Field. *Proceedings of the Water Environment Federation* **2012**, 4532–4588 (2012).