Solar + Storage + IoT + LED = $30 Trillion

Technological disruptions in energy systems

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All images from Wikipedia unless otherwise specified
Global energy consumption 2013

- Fossil Fuels = 87%
- Oil: 30%
- Gas: 4%
- Coal: 7%
- Nuclear: 1%
- Hydro: 24%
- Wind: 33%
- Solar: 0%
- Geothermal & biomass: 0%
- Biofuels: 1%

Energy Matters
ruanmearns.com
BP 2014 data
But we have a choice...
25 April 1954
Bell Laboratories
Chapin, Fuller and Pearson.
From a solar cell to a PV System

PV-System

- Electricity Meter
- AC Isolator
- Fusebox
- Inverter
- Battery
- Charge Controller
- Generation Meter
- DC Isolator
- Cabling
- Mounting
- Tracking System
Topaz solar farm, California 25.6 km² 9 million panels
Solar PV is growing as fast as cell phones.
Positive feedback loop

The more you ship

The cheaper it gets
Price history of silicon PV cells in US$ per watt

Source: Bloomberg New Energy Finance & pv.energytrend.com
Unsubsidized Levelized Cost of Energy Comparison

Certain Alternative Energy generation technologies are cost-competitive with conventional generation technologies under some scenarios; such observation does not take into account potential social and environmental externalities (e.g., social costs of distributed generation, environmental consequences of certain conventional generation technologies, etc.) or reliability-related considerations (e.g., transmission and back-up generation costs associated with certain Alternative Energy technologies).

[Graph showing levelized cost comparison between Alternative Energy and Conventional energy sources.]

Actual Low-Price Bid from Masdar Consortium in 2016

Source: Lazard estimates.

Note: Here and throughout this presentation, unless otherwise indicated, analysis assumes 60% debt at 8% interest rate and 40% equity at 12% cost for both conventional and Alternative Energy generation technologies. Assumes diesel price of ~$2.50 per gallon, Northern Appalachian bituminous coal price of ~$2.00 per MMBtu and a natural gas price of ~$3.50 per MMBtu for all applicable technologies other than Natural Gas Reciprocating Engine, which assumes ~$3.50 per MMBtu. Analysis does not reflect potential impact of evolving regulations/rules promulgated pursuant to the EPA's Clean Power Plan. See following page for footnotes.

Denotes distributed generation technology.
3 characteristics of solar generation

1. Sunlight is free!
   - Near-zero OPEX, all cost is CAPEX
3 characteristics of solar generation

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2. 20-25 year nearly maintenance-free lifetime
3 characteristics of solar generation

1. Sunlight is free!
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2. 20-25 year nearly maintenance-free lifetime

3. Amount of generation over lifetime depends on geography
Levelized Cost of Energy
Levelized Cost of Energy

Effective cost per kWh (units of energy)
Levelized Cost of Energy

CAPEX
$/kWp
(Dollars per 1000 watts)
Levelized Cost of Energy

Average cost per unit of energy over 20y lifetime

$/kWh

CAPEX

$/kWp

*$Assumes a fixed equipment lifetime
**Levelized Cost of Energy**

Average cost (over lifetime) $/kWh

1000 KWh produced over lifetime

$1/KWh

CAPEX $/kWp

*Assumes a fixed equipment lifetime*
Impact of CAPEX reduction

Average cost $/kWh

- $1/KWh
- $0.8/KWh

CAPEX $/kWp

1000 KWh produced over lifetime

Swanson’s Law

- $800
- $1000
Impact of geography

Average cost $/kWh

$1/KWh

$0.5/KWh

Incoming solar radiation kWh/kWp.year

North Germany

France

Southwest US

Saudi Arabia

Initial cost $/kWp

$1000

$1000

$1000
Compare to conventional

- Average cost: $/kWh
- Cost of conventional grid energy: $0.1/KWh
- Initial cost: $/kWp

- Insolation: kWh/kWp.year
  - North Germany
  - France
  - Southwest US
  - Saudi Arabia
CAPEX trend

Average cost
$/kWh

Cost of conventional grid energy

Insolation
kWh/kWp.year

Initial cost
$/kWp

Swanson's Law

North Germany
France
Southwest US
Saudi Arabia
Solar wins! Everywhere!
The solar revolution ...
... will be led by the accountants
Unfortunately...

Problem 1: No sun at night...
Solution: use solar by day and grid by night
Problem 2: excess solar generation

8 May 2016, Germany (from Agora Energiewende)
Solution: use ‘free energy’ for something
Problem 3: Variability

Solution: storage

Storage decouples supply and demand
Storage is hot...

Global investment in energy storage technologies to reach $122 Billion by 2021

Source: Pike Research
Tesla/Panasonic and GM/LG Chem battery costs are already (in 2016) down to the lowest projections for 2020!
Positive feedback loop

The more you ship
The cheaper it gets
Why?
Nissan Leaf chassis
Tesla gigafactory

<table>
<thead>
<tr>
<th>Gigafactory Projected Figures</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020 Tesla Vehicle Volume</td>
</tr>
<tr>
<td>2020 Gigafactory Cell Output</td>
</tr>
<tr>
<td>2020 Gigafactory Pack Output</td>
</tr>
<tr>
<td>Space Requirement</td>
</tr>
<tr>
<td>Total Land Area (acres)</td>
</tr>
<tr>
<td>Employees</td>
</tr>
</tbody>
</table>

New Local Renewables
Solar and Wind
Annual EV sales

*Includes Battery as well as Hybrid Electric Vehicles

Source: EvSales.blogspot.com
Positive feedback loop

The more you ship
The cheaper it gets
EVs in Canada

Electric Vehicle Sales in Canada
Year-to-Year Comparison

From Fleetcarma.com, Feb 2017
Other uses of storage
Reducing curtailment
In other news...
Building lighting accounts for 30% of building electricity use

Cost: $230 Billion/year
Incandescent : CFL : LED
10 : 2 : 1
LED cost projection
Global Lighting Market

Lamps – Annual Unit Shipments & Penetration

- Annual shipments of 14B units – declining to 10B due to longer lifetime of LED Bulbs
- All lighting technologies flat, except incandescents that will decline
- LED experiencing explosive growth and capture 25% share by 2017
Positive feedback loop

The more you ship
The cheaper it gets
To sum up...

Solar, storage, and LEDs are all declining exponentially in price.
But something is missing...
Sensing and control
Why?
Conventional grid
Future grid
Future grid
Need to forecast, monitor and control...
Internet of Things
Micro sensors
Pervasive communication
Pervasive control
IoT allows pervasive communication, sensing, computation, control
The 50 billion question

Worldwide number of internet-connected devices, forecast, bn

- Fixed communications
- Mobile communications
- Computers
- Consumer electronics and medical devices
- Industrial devices*
- Automotive

Source: Cisco

*Includes military and aerospace

Source: The Economist
Positive feedback loop

The more you ship
The cheaper it gets
O wonder!
How many goodly creatures are there here!
How beauteous mankind is! O brave new world,
That has such people in't.

ACT V SCENE II, THE TEMPEST, W. SHAKESPEARE
Renewable generation to reduce carbon footprint
Demand-side management to reduce peak/average ratio
Storage management

Storage to decouple supply and demand

Source: European Technology Platform Vision Document
Sensing, communication, and control
$30 Trillion economic activity!

*displaced over 20 years and very approximate numbers
Fuel cost of transportation: $3.5 Trillion/year
1.05 Trillion/yr

30% solar-powered transportation
Electric Utility Annual Revenues:

1 Trillion/year
0.5 Trillion/yr

Utilities 50% solar/wind supply

1.05 Trillion/yr

30% solar-powered transportation
IoT spending
= 10% of revenue
= 0.1 Trillion/year
0.1 Trillion/yr

IoT spending

0.5 Trillion/yr

Utilities 50% solar/wind supply

1.05 Trillion/yr

30% solar-powered transportation
Cost reduction from LED lighting: $0.2 Trillion/year
0.2 Trillion/yr
Demand-side savings from LED lighting

0.1 Trillion/yr
IoT spend

0.5 Trillion/yr
Utilities 50% solar/wind supply

1.05 Trillion/yr
30% solar-powered transportation
$1.85$ Trillion/year of economic disruption

- $1.05$ Trillion/yr: 30% solar-powered transportation
- $0.5$ Trillion/yr: Utilities 50% solar/wind supply
- $0.25$ Trillion/yr: Demand-side savings from LED lighting
- $0.2$ Trillion/yr: IoT spend
- $0.1$ Trillion/yr: Economic disruption
$ 37 Trillion economic activity!

*over 20 years
I’m lying...
Well, perhaps not
Buffett Ready to Double $15 Billion Solar, Wind Bet

China Aims to Spend at Least $360 Billion on Renewable Energy by 2020

Apple Invests $3 Billion in Solar Energy

By Bill Gates: Why I’m investing $1 billion of my own money into clean energy research

Japan to Invest $20 Billion in Indian Solar Power
Goal: 1TW by 2030

Power minister Piyush Goyal and French environment minister Segolene Royal announced the solar finance programme that aims to lower the cost of finance and facilitate the flow of more than $1 trillion investment to members of the International Solar Alliance (ISA).
Information Systems and Science for Energy Laboratory
Mission

To use information systems and science to

- increase the efficiency
- reduce the carbon footprint

of energy systems
Grid  Internet

Electrons  =  Bits
Load  =  Source
Transmission line  =  Communication link
Battery/energy store  =  Buffer
Demand response  =  Congestion control
Stochastic generator  =  Variable bit rate source
Contexts
- Smart homes and buildings
- Distribution networks
- Distributed generation

New technologies
- Solar and wind
- Storage
- Electric vehicles
- LED lighting
- Pervasive computation and communication

Approaches
- Internet-inspired
- Energy system design
- Data-driven analysis
- Optimization
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A pond fills with pond scum. The scum doubles daily. The pond fills on the 30th day.

When is the pond half full?
Acknowledgments