An Industrial Perspective on the Energy Challenges of Today

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Cores and Castings
GE Power

Meet The Energy Leaders
TU Delft
November 17, 2017
An item of interest from reading the news on the way over

Nelson Bryant (USA) receiving from André Duijghuisen (NL) the knife he lost when parachuting into the Netherlands on Sept 17, 1944.
Agenda

• GE’s role in power generation
• Is the future like the past in power generation?
• Two awesome power technologies
• Fossil fuels vs renewable energy
• What choice would you make?
GE Power – equipment for any fuel, any region, any need

- $49B revenue
- Expansive global reach... >150 countries
- Leading technology, >1/3 of the world’s power
- ~2,500 GW installed capacity
- >950,000 installed assets
- #1 gas turbine supplier, #4 steam, #2 wind
What is the future of Power Generation?
How did Aviation thinks its future would change in 50 yrs?

**Speculation**

*de Havilland Comet, 1946*

**Reality**

*Boeing 787 Dreamliner, 2016*

How much will Power and Aviation change in the next 50 years? What technologies will win and lose?
Power generation orders in the last 50 years

By region
- China
- Asia
- Middle East & Africa
- South & Central America
- North America
- Europe

By technology
- Steam Plant
- GT Plant
- Nuclear
- Hydro
- Wind
- Solar
- Geothermal
- Biomass
- Renewable

First Nuclear Wave

Global boom

1970s oil crisis

US boom

China boom

Financial Crisis

GW/yr

Order/year

Two awesome technologies:

1. Gas Turbines
GE 9HA Gas Turbine
Gas Turbine Combined Cycle for Power Generation

- Air
- Natural Gas
- Gas Turbine
- Hot Exhaust
- Power
- Generators
- Steam Turbine
- Steam
THE HEART OF A COMBINED CYCLE POWER PLANT IS THE GAS TURBINE

- Low installation cost
- Low operating cost
- Natural gas fired
- Cleaner burning
- From 5 to 600 MW
- Highly efficient
- Starts quickly
- Follows loads easily
How do you ship something that weighs 800 tons?
World’s Most Efficient Power Plant

EDF Bouchain in France
GE 9HA.01, 605-MW

62.22%
Turbine Blades: My Current Area of Focus

- Turbine blades
  - key to high performance
  - cast from high-temperature super alloys
  - complex internal passages for cooling flow
  - created by ceramic core inserts during casting
GE Cores and Castings: State of the Art facility for the design and development of gas turbine cores and blades
Wax in injected around the 3D advanced core in the exact shape of the blade and wax patterns are assembled for shelling
Wax trees are dipped in multiple layers of ceramic slurry
Multiple layers make a complete shell, and the internal wax is melted and removed.
The shell is filled in a vacuum furnace with molten alloy that solidifies into a single crystal.
Removing the ceramic shell and leaching out the internal core reveals the gas turbine blade within
A CT scan shows the detail of the complex internal cooling passages.
An awesome piece of machinery
Even better, efficient gas turbines are replacing coal for power generation, in the US and elsewhere...

Figure 7.2  Electricity Net Generation  
(Billion Kilowatthours)

Total (All Sectors), Major Sources, 1949–2016

- Coal
- Natural Gas
- Nuclear Electric Power
- Petroleum
- Renewable Energy*

Reduction in coal use
And help reduce GHG emissions in the US

*The switch to natural gas and better efficiency have the biggest impact*
To everyone’s surprise, the US has been reducing GHG intensity
As engineers and scientists, we need to ensure we stay credible here.

Global warming is a matter of fact, not faith
Facts confirm climate change
Letter To The Editor | October 16, 2017

In an Oct. 9 letter criticizing an earlier letter to the editor, Bob Lindinger said he was “not a global warming believer or a global warming denier...” I found his choice of the word “believer” an interesting one, since it implies that global temperatures are something that can’t be measured, but must rather be taken on faith.

Personally, I use a device called a thermometer to measure temperature. It tends to take all the believing and non-believing out of the process.

Mr. Lindinger went on to say, “Climate change proponents have made their cause a matter of faith” (again, an interesting choice of words), citing “a great physicist like...
How do you measure the temperature of a gas turbine combustor?
How do you measure the temperature of the earth?
Two awesome technologies:

2. Wind Turbines
GE is big in Renewable Energy

Onshore Wind
- 35,000 turbine
- #2 Global supplier

Offshore Wind
- Setting the benchmark for the marine energies industry
- First US offshore site

Hydro
- Collaborating with customers as a leading player in the hydropower market

LM Wind Power
- Insourcing blade mfg. to strengthen GE's supply chain

$10B sales, 80+ countries, 22,000 employees, 400GW installed base
GE wind turbines are awesome machines...

**GE’s 2.0-116 onshore turbine**

- 2 MW and 116m rotor diameter
- 53.3% gross capacity factor at 7.5 m/s
- 57 meter blades
- 127m tower heights
- sophisticated technology for loads, wake control, and reliability
...and I love climbing them and spreading the word
...and I thought you might enjoy a brief tour
But they weren't always awesome:
GE gradually replaced everything with our designs, internal manufacture

Redesigned systems introduce GE technology
And the result was a huge increase in turbine availability.

Core Fleet Performance equal to output of 4,000 turbines.
Why renewable energy will be small, even if we want it to be big, and fossil fuel will be big, even if we want it to be small.
Wind and Solar costs keep dropping and installations keep growing

Wind Power cost (¢/kWH)

Cumulative (GW)

~15
~12
~9.5
283
~6.5
<5
~415GW

Solar PV installed cost ($/watt)

Cumulative (MW)

7
$3.24
$1.30
$0.97
$0.79

And countries keep setting records for wind and solar output
So why do electricity prices keep going up?

Composition of average power price in ct/kWh for a household using 3,500 kWh per year, 2006 - 2017.


- Renewable fee
- Grid fee
- Generation fee
Renewables is *duplicate* capacity not *additional* capacity.

- What is the *minimum*, not the *maximum*?
- Conventional fuels are used less but everything still needed as backup.
Even renewable energy advocates like me want reliable power.

I don’t want to use my factory just 32% of the time.

I don’t want to turn off appliances on calm days?

I won’t buy a car that starts just 11% of the time?

The reality is, you and I need dependable power.
In addition, wind and solar put pressure on the grid...

- Mid-day excess solar power can drive conventional production and prices down
- Conventional sources must ramp power quickly as sun sets
...and put pressure on conventional power producers

- RWE pays for the same assets but gets less revenue.
- Can Germany allow RWE to go bankrupt?
But what about storage?

As costs come down, opportunities go up.
But even significant battery storage has a small impact on overall grid

- 20% solar and wind
- Potential for 4GW to battery storage early in day
  - $4.5B
  - appx 2x total global capacity today
- 14.7 GWhr of shift that day
  - 3% of total CA annual demand
- Need smaller peak in conventional production later in day.
- Gas turbine capacity factor drops from 46 to 43%

* Based on CAISO data. 231 TWH of total annual load in 2016, with ~13% coming from solar and 7% from wind generation. Renewable generation based on CAISO daily renewables watch for July 27 2016.
Renewables costs are getting competitive

Equipment and installation cost

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<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Coal</td>
<td>2003</td>
<td>3</td>
<td>4.664</td>
<td>1.07</td>
<td>1.083</td>
<td>0.507</td>
<td>0.095</td>
<td>0.571</td>
<td>5.790</td>
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<tr>
<td>Nat gas</td>
<td>2003</td>
<td>4</td>
<td>3.656</td>
<td>1.07</td>
<td>1.083</td>
<td>0.507</td>
<td>0.095</td>
<td>0.571</td>
<td>5.790</td>
</tr>
<tr>
<td>Nuclear</td>
<td>2003</td>
<td>5</td>
<td>3.656</td>
<td>1.07</td>
<td>1.083</td>
<td>0.507</td>
<td>0.095</td>
<td>0.571</td>
<td>5.790</td>
</tr>
<tr>
<td>Wind</td>
<td>2003</td>
<td>6</td>
<td>3.656</td>
<td>1.07</td>
<td>1.083</td>
<td>0.507</td>
<td>0.095</td>
<td>0.571</td>
<td>5.790</td>
</tr>
<tr>
<td>Solar PV</td>
<td>2003</td>
<td>7</td>
<td>3.656</td>
<td>1.07</td>
<td>1.083</td>
<td>0.507</td>
<td>0.095</td>
<td>0.571</td>
<td>5.790</td>
</tr>
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</table>

Operating cost

<table>
<thead>
<tr>
<th>Technology</th>
<th>Fixed O&amp;M ($/MWhr)</th>
<th>Variable O&amp;M ($/MWhr)</th>
<th>Total O&amp;M ($/MWhr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>35</td>
<td>35</td>
<td>70</td>
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<tr>
<td>Nat gas</td>
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<tr>
<td>Wind</td>
<td>12</td>
<td>12</td>
<td>24</td>
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<tr>
<td>Solar PV</td>
<td>9</td>
<td>9</td>
<td>18</td>
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But, again, is cheap intermittent power as good as expensive reliable power?
Consequently, renewables is growing fast but is a small slice of total pie
Competing objectives:
What problem are you trying to solve?
What would you do?
Problem 1: Human suffering

*The Economist, Chart of the Day, November 8, 2017*

**Africa**
- more people in Ethiopia have cell phones than access to electricity
- ~600,000/yr die from indoor cooking

**India**
“It’s a matter of shame that 68 years after independence we have not been able to provide a basic amenity like electricity.”
- Piyush Goyal, Minister of Power, India
Problem 2: Long term global impact
So, what would you do with $1B?

<table>
<thead>
<tr>
<th>choice of power source</th>
<th>households that will get power</th>
<th>availability of that power</th>
<th>fuel cost</th>
<th>availability of fuel</th>
<th>greenhouse gas impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>coal</td>
<td>700,000</td>
<td>98%</td>
<td>$4/MWhr</td>
<td>good</td>
<td>very high</td>
</tr>
<tr>
<td>natural gas</td>
<td>1,900,000</td>
<td>98%</td>
<td>$3/MWhr</td>
<td>pipeline or LNG tanker</td>
<td>high/moderate</td>
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<tr>
<td>nuclear</td>
<td>350,000</td>
<td>98%</td>
<td>$1/MWhr</td>
<td>good</td>
<td>none</td>
</tr>
<tr>
<td>solar</td>
<td>880,000</td>
<td>15%</td>
<td>free</td>
<td>most locations</td>
<td>none</td>
</tr>
<tr>
<td>solar - with storage</td>
<td>40,000</td>
<td>70%</td>
<td>free</td>
<td>most locations</td>
<td>none</td>
</tr>
</tbody>
</table>

The answer is not obvious
My guess is that the future will not be too different from the past.
All this and more will be part of the solution.

• Remarkable advances in the past; progress still being made
• We will need multiple options
• And engineers like us will be part of the solution
Thank you