An Industrial Perspective on the Energy Challenges of Today

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James Maughan
Senior Executive and General Manager
Cores and Castings
GE Power

Meet The Energy Leaders
TU Delft
November 17, 2017

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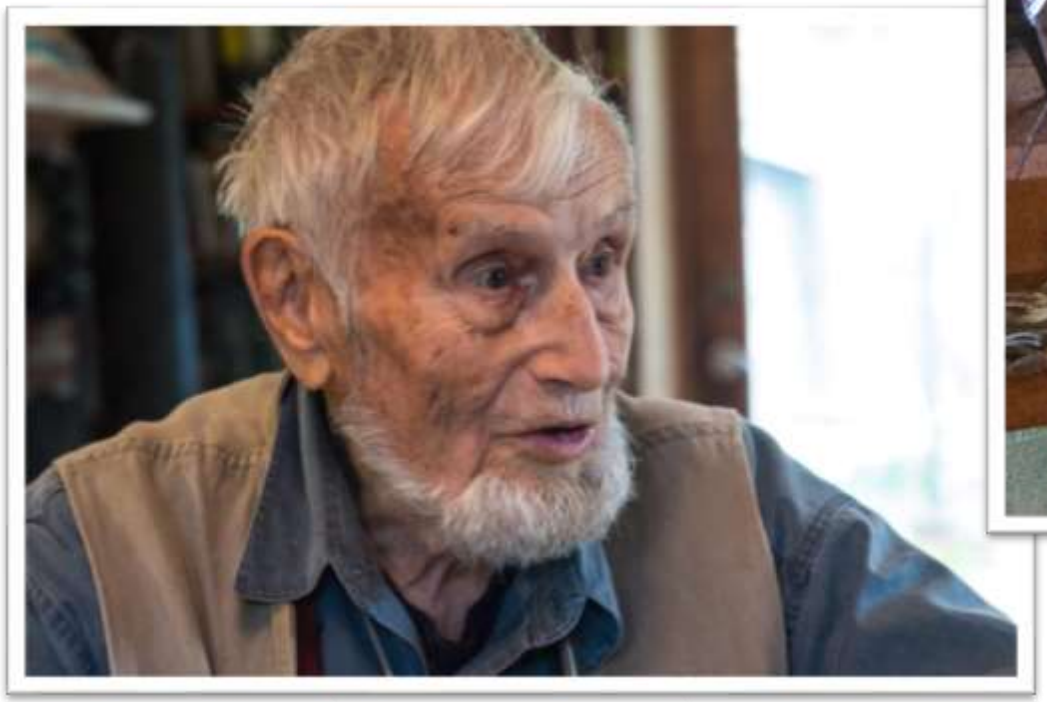
An item of interest from reading the news on the way over



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?

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GE Power

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GE Power – equipment for any fuel, any region, any need

AERO ENGINES

SOLAR PV

GAS TURBINES

ONSHORE WIND

GE HITACHI NUCLEAR

POWER CONVERSION

OFFSHORE WIND

STEAM TURBINES

PLANT EQUIPMENT

HYDRO

- $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

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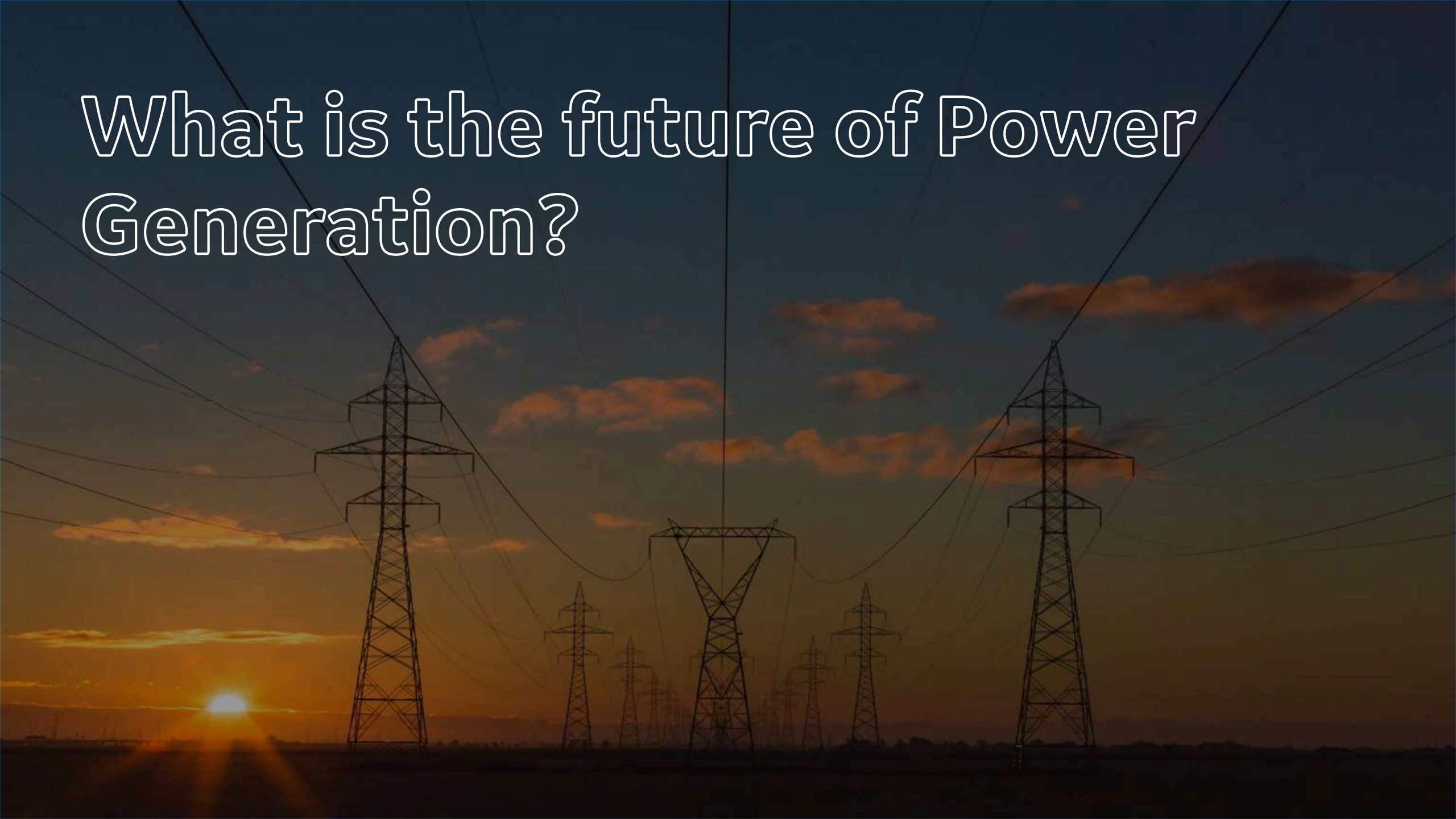
What is the future of Power Generation?



How did Aviation thinks its future would change in 50 yrs?

de Havilland Comet, 1946

Speculation

Reality

Boeing 787 Dreamliner, 2016

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

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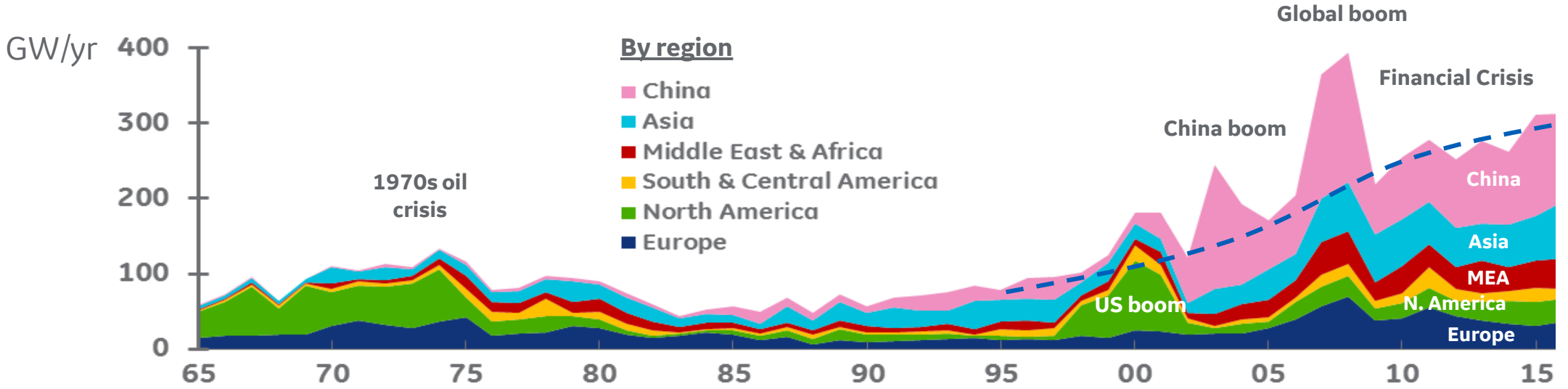
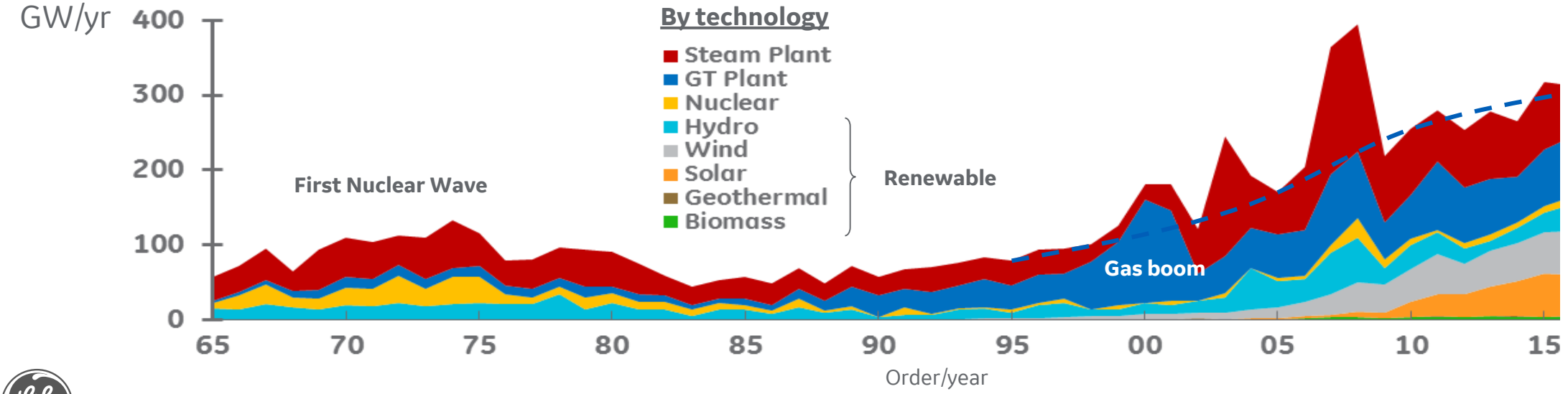
Power generation orders in the last 50 years



The Future ?



The Future ?

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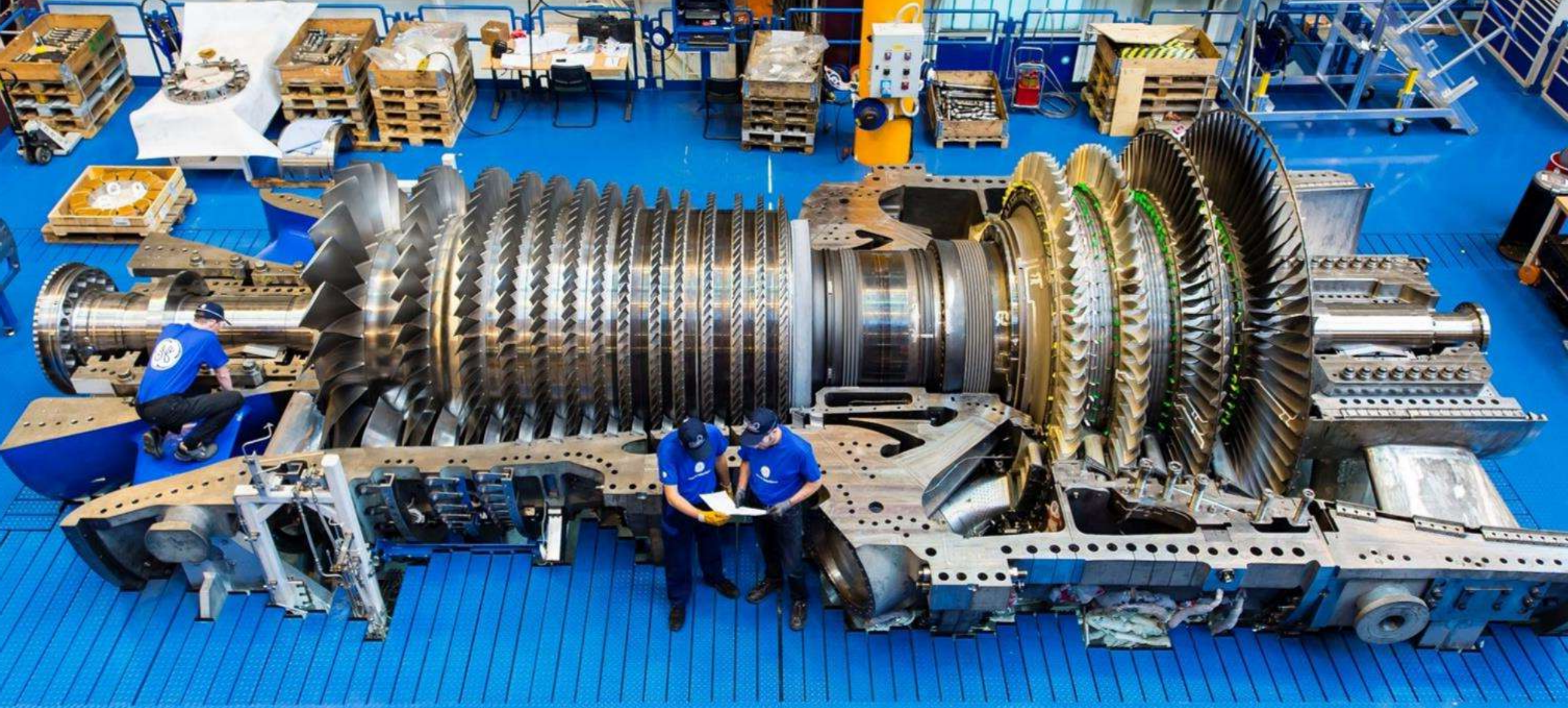
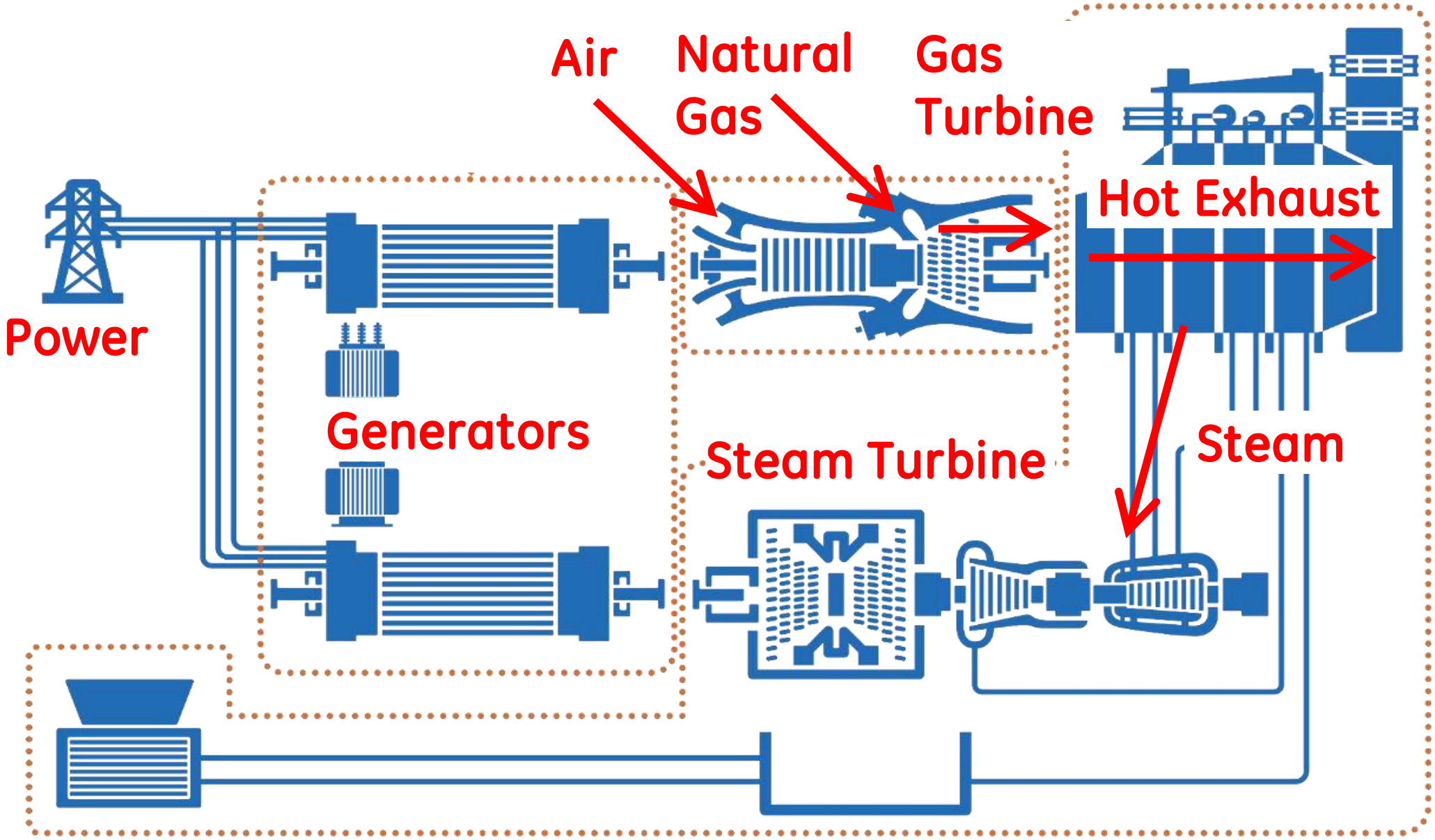
Two awesome technologies:
1. Gas Turbines



GE 9HA Gas Turbine

Gas Turbine Combined Cycle for Power Generation



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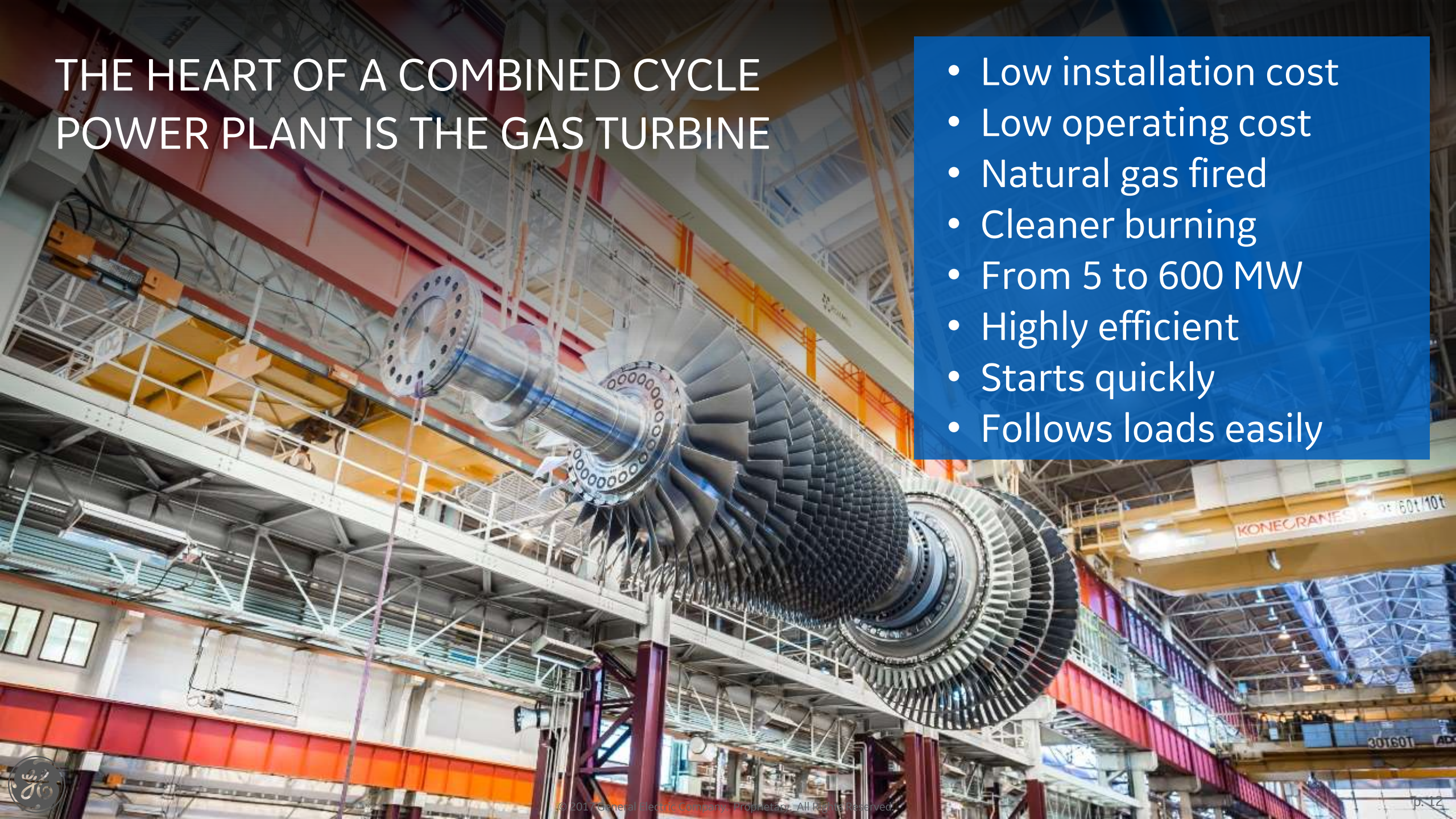
THE HEART OF A COMBINED CYCLE POWER PLANT IS THE GAS TURBINE



- Low installation cost
- Low operating cost
- Natural gas fired
- Cleaner burning
- From 5 to 600 MW
- Highly efficient
- Starts quickly
- Follows loads easily

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How do you ship something that weighs 800 tons?

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World's Most Efficient Power Plant

62.22%

EDF Bouchain in France

GE 9HA.01, 605-MW

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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

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GE Cores and Castings: State of the Art facility for the design and development of gas turbine cores and blades

GE Plant, Bldg 66, Schenectady, NY

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Wax in injected around the 3D advanced core in the exact shape of the blade and wax patterns are assembled for shelling

Thumbnail video

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Wax trees are dipped in multiple layers of ceramic slurry

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Multiple layers make a complete shell, and the internal wax is melted and removed.

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The shell is filled in a vacuum furnace with molten alloy that solidifies into a single crystal

hot shell on plate from below

metal pour

shell after casting

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Removing the ceramic shell and leaching out the internal core reveals the gas turbine blade within

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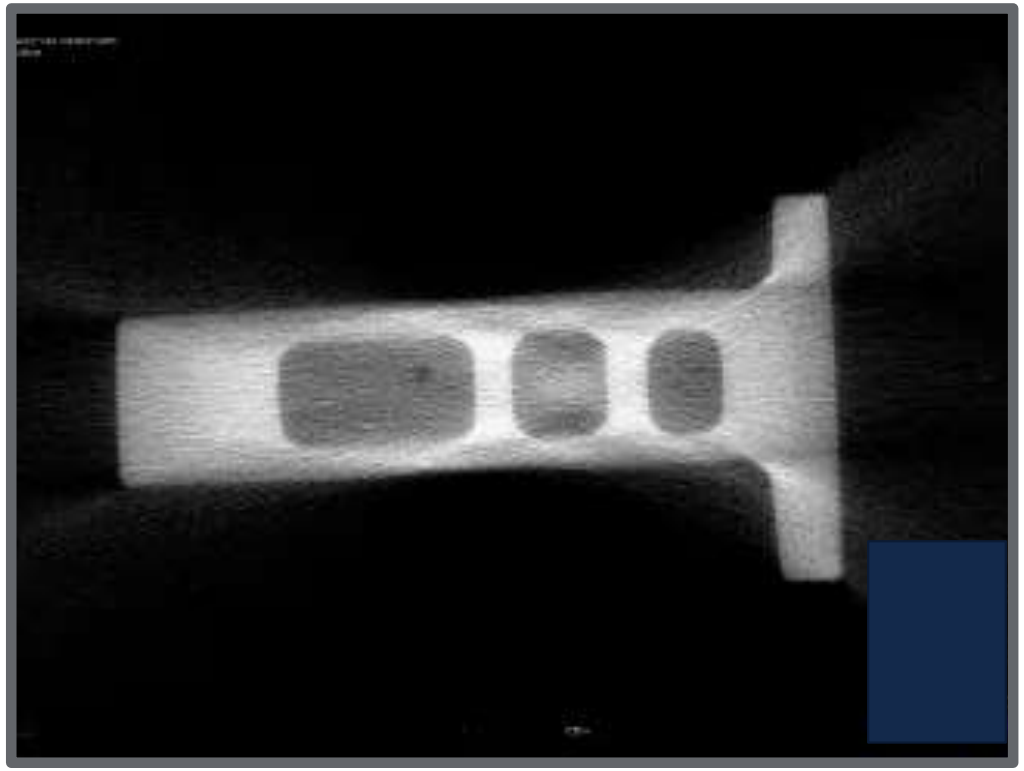
A CT scan shows the detail of the complex internal cooling passages



Thumbnail video of 7HA casting
- root to tip

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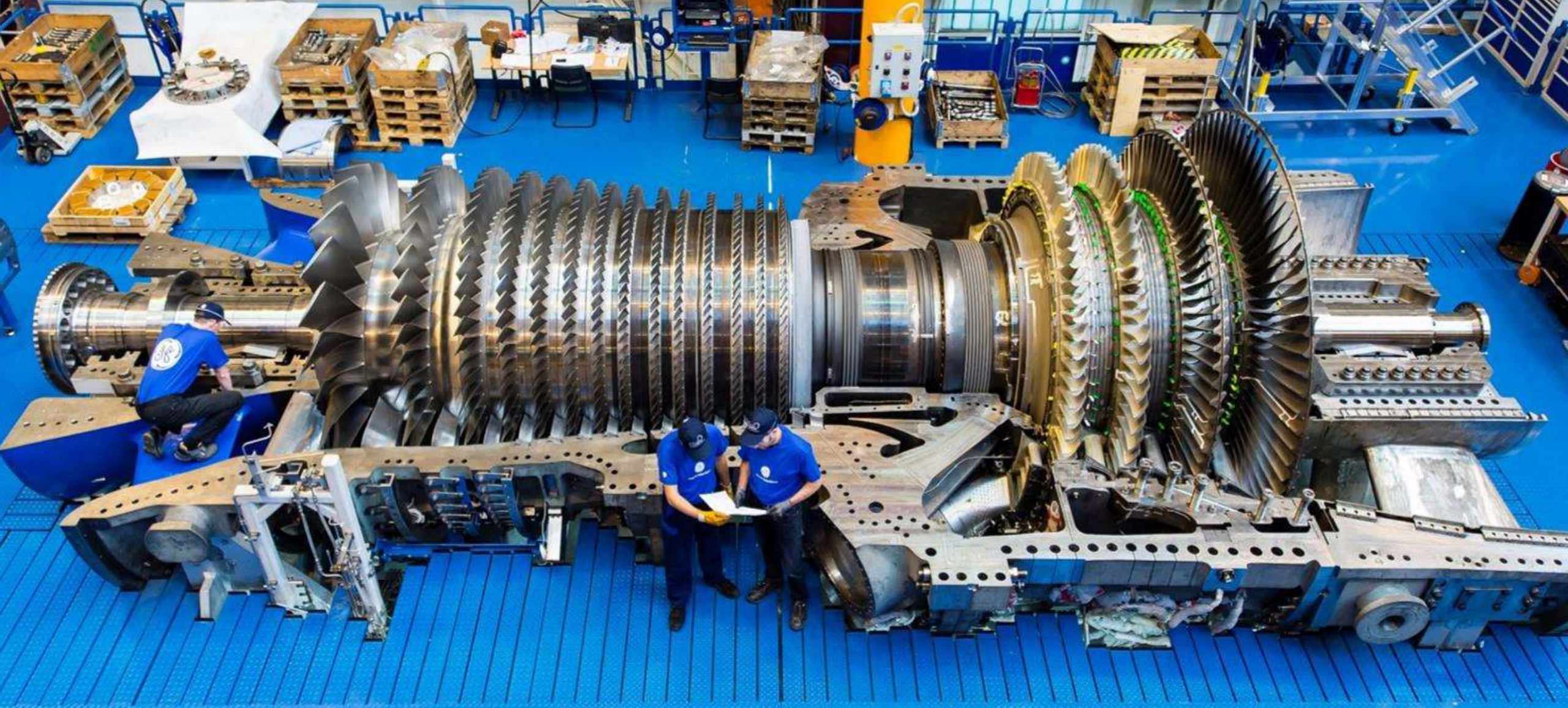

An awesome piece of machinery

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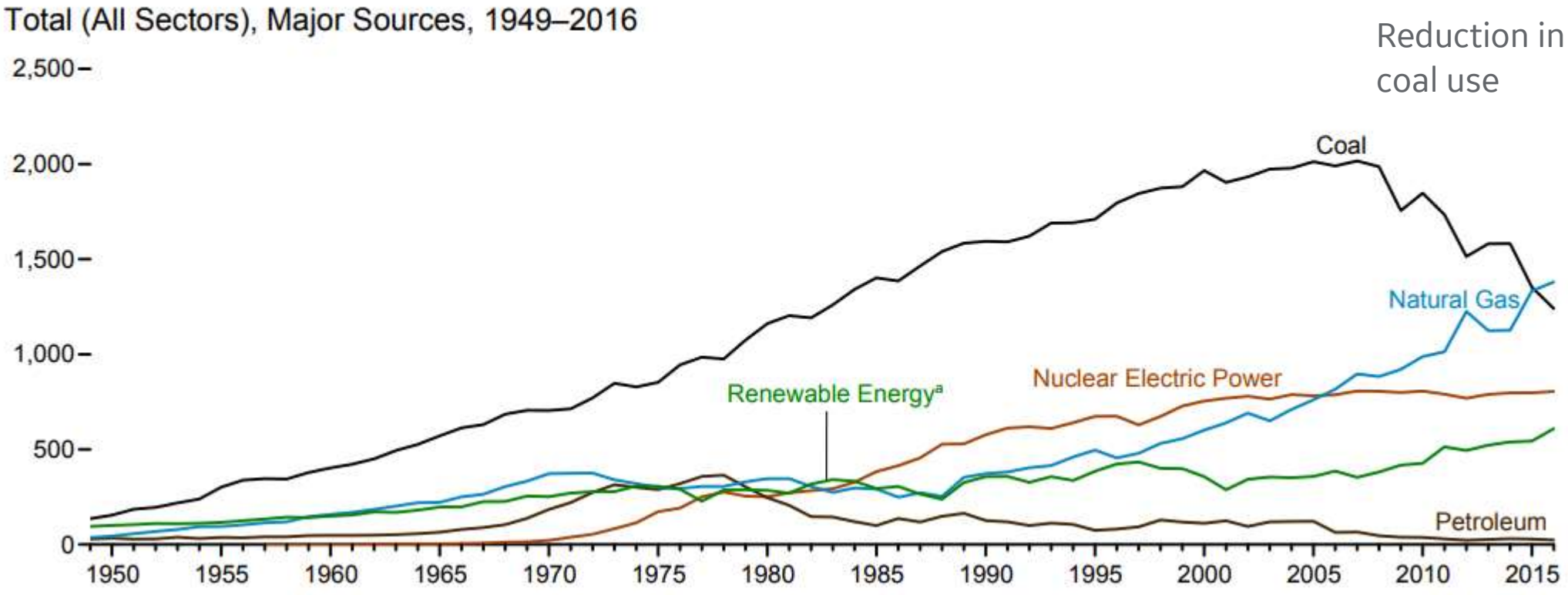
Even better, efficient gas turbines are replacing coal for power generation, in the US and elsewhere…

Figure 7.2 Electricity Net Generation
(Billion Kilowatthours)



Reduction in coal use

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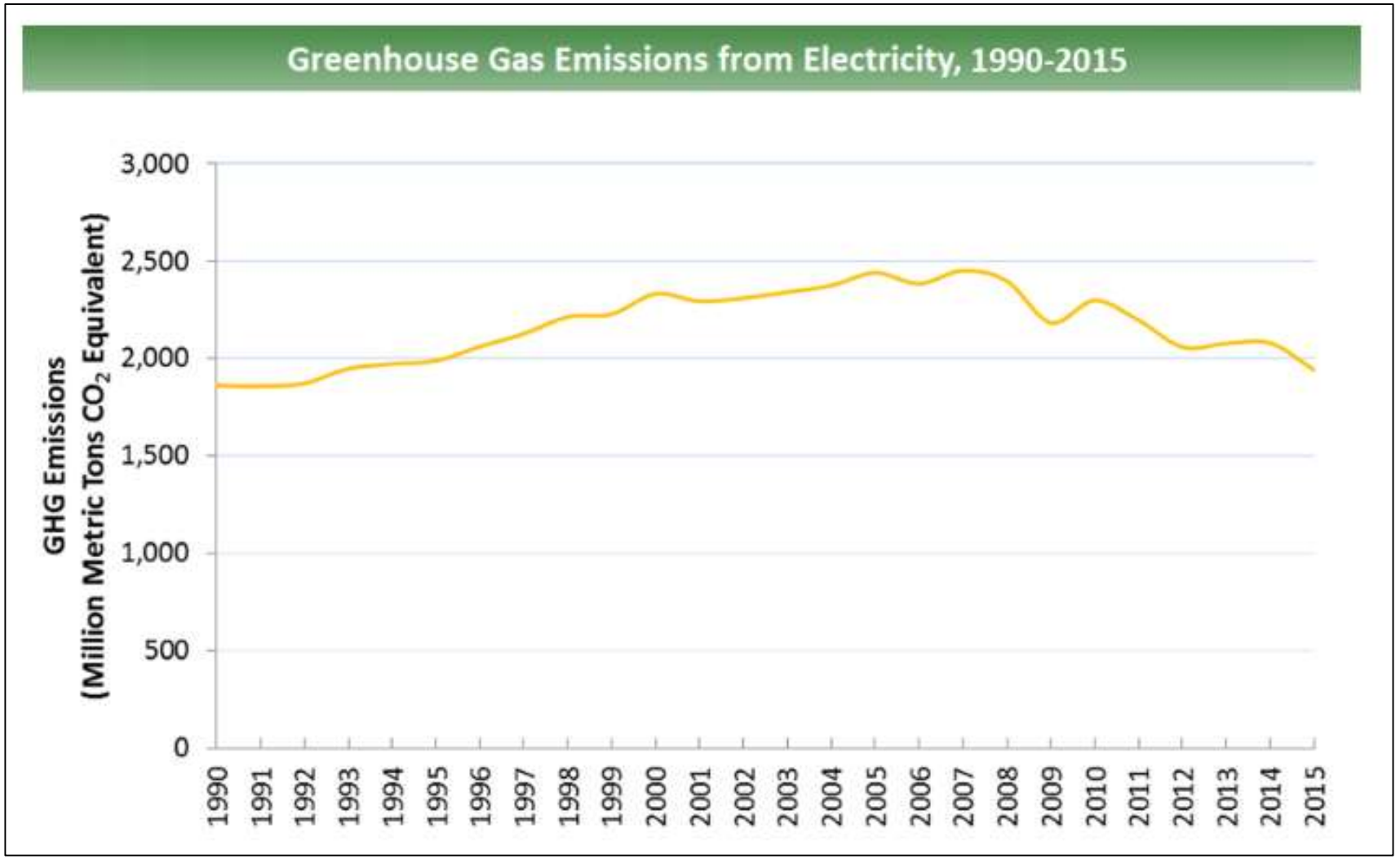
And help reduce GHG emissions in the US

The switch to natural gas and better efficiency have the biggest impact



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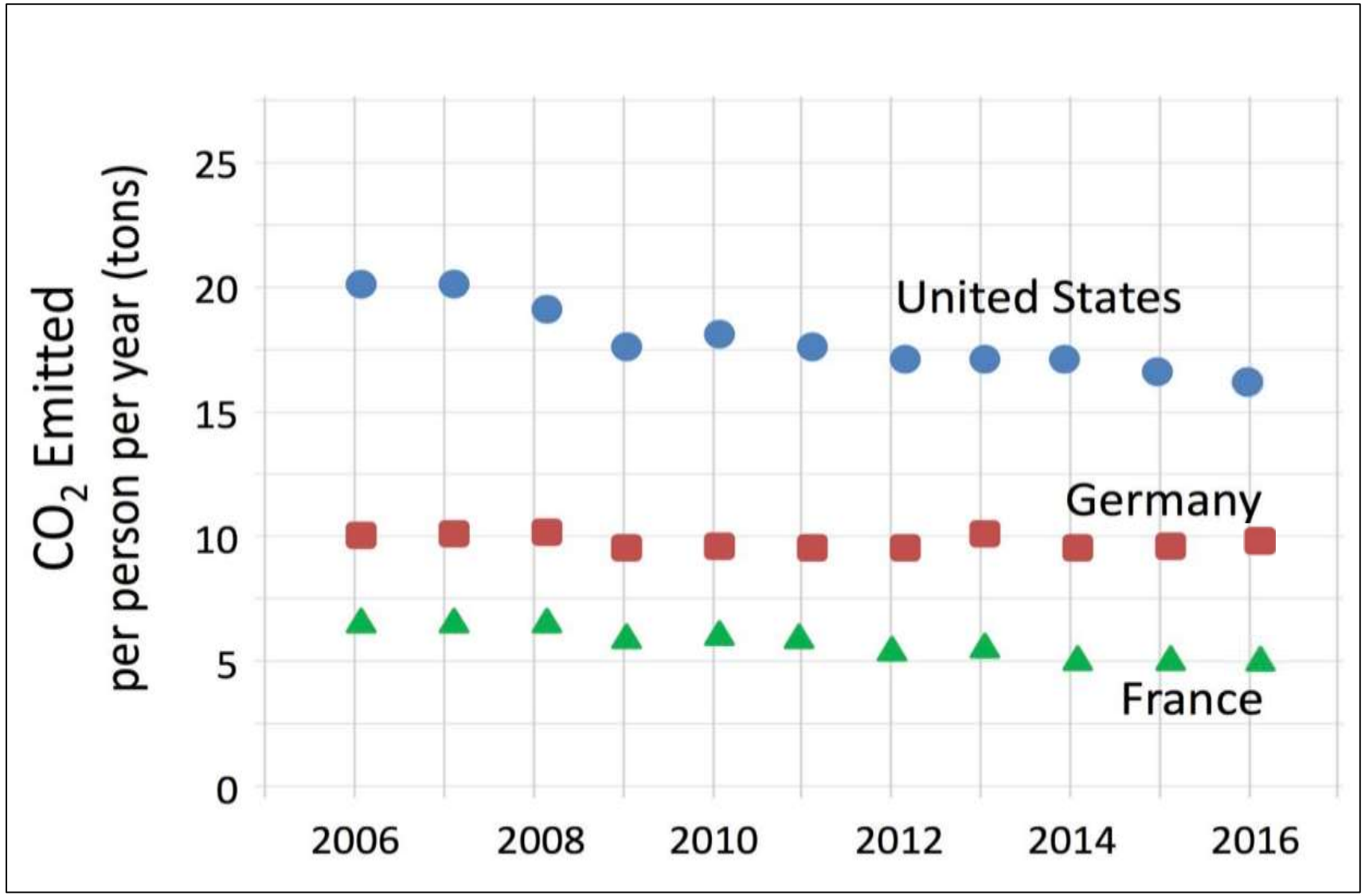
To everyone's surprise, the US has been reducing GHG intensity



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A recent letter from the local paper with dialogue on global warming

Global warming is a matter of fact, not faith

Facts confirm climate change

Letter To The Editor | October 16, 2017

THE DAILY GAZETTE

THE DAILY GAZETTE | Thursday, November 2, 2017

OPINION

SHARE

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

As engineers and scientists, we need to ensure we stay credible here

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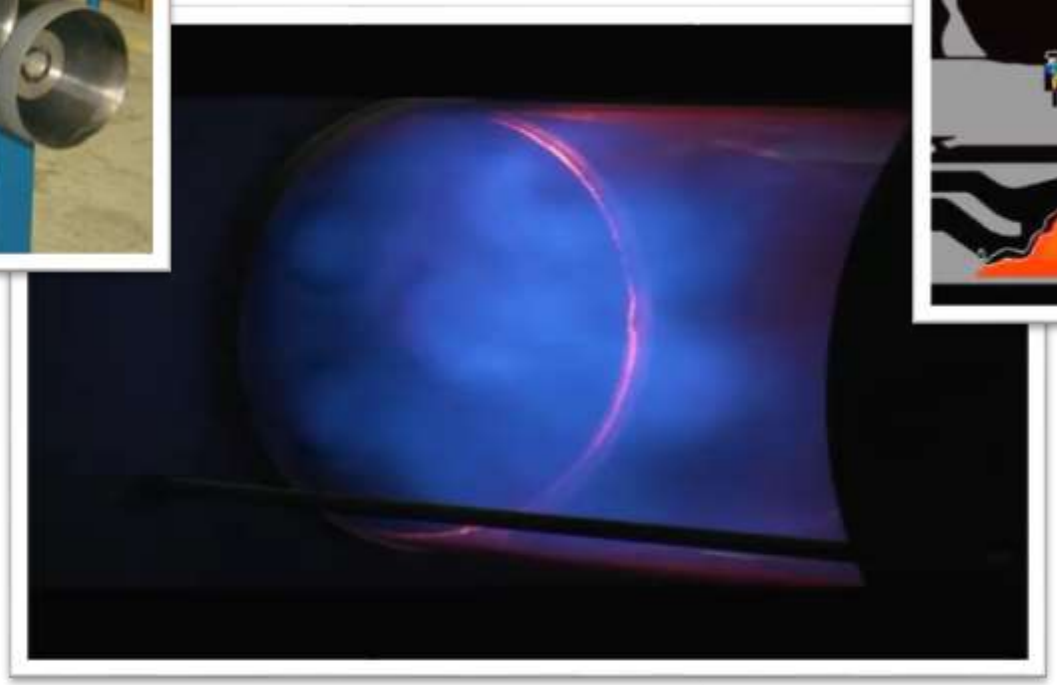
How do you measure the temperature of a gas turbine combustor?



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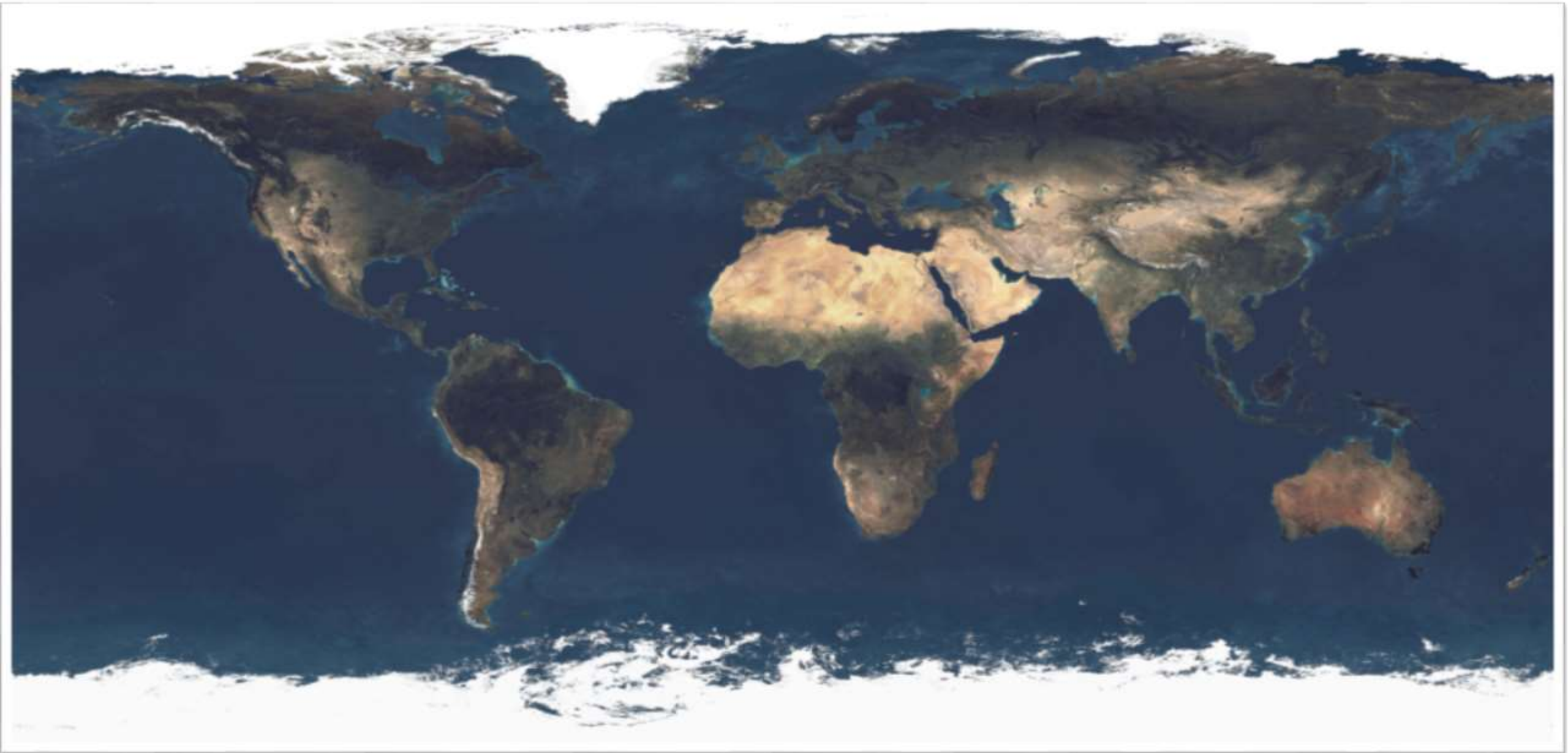
How do you measure the temperature of the earth?




Two awesome technologies:
2. Wind Turbines

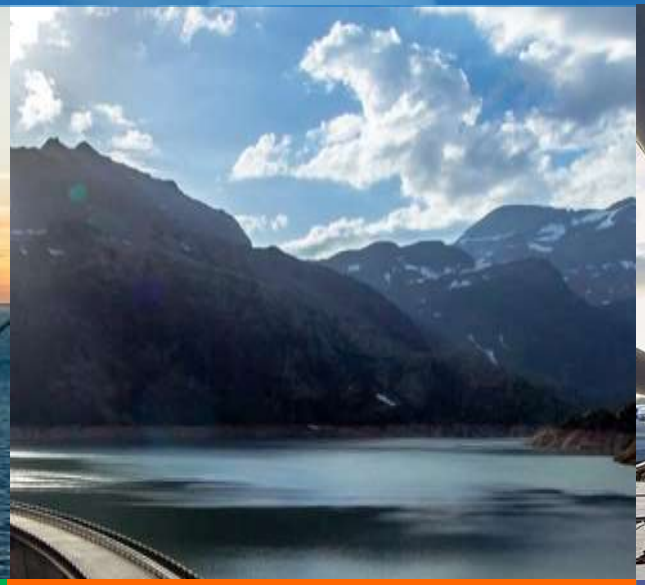
GE is big in Renewable Energy

Onshore Wind

35,000 turbine
#2 Global supplier

Offshore Wind

Setting the benchmark
for the marine energies industry
First US offshore site



Hydro

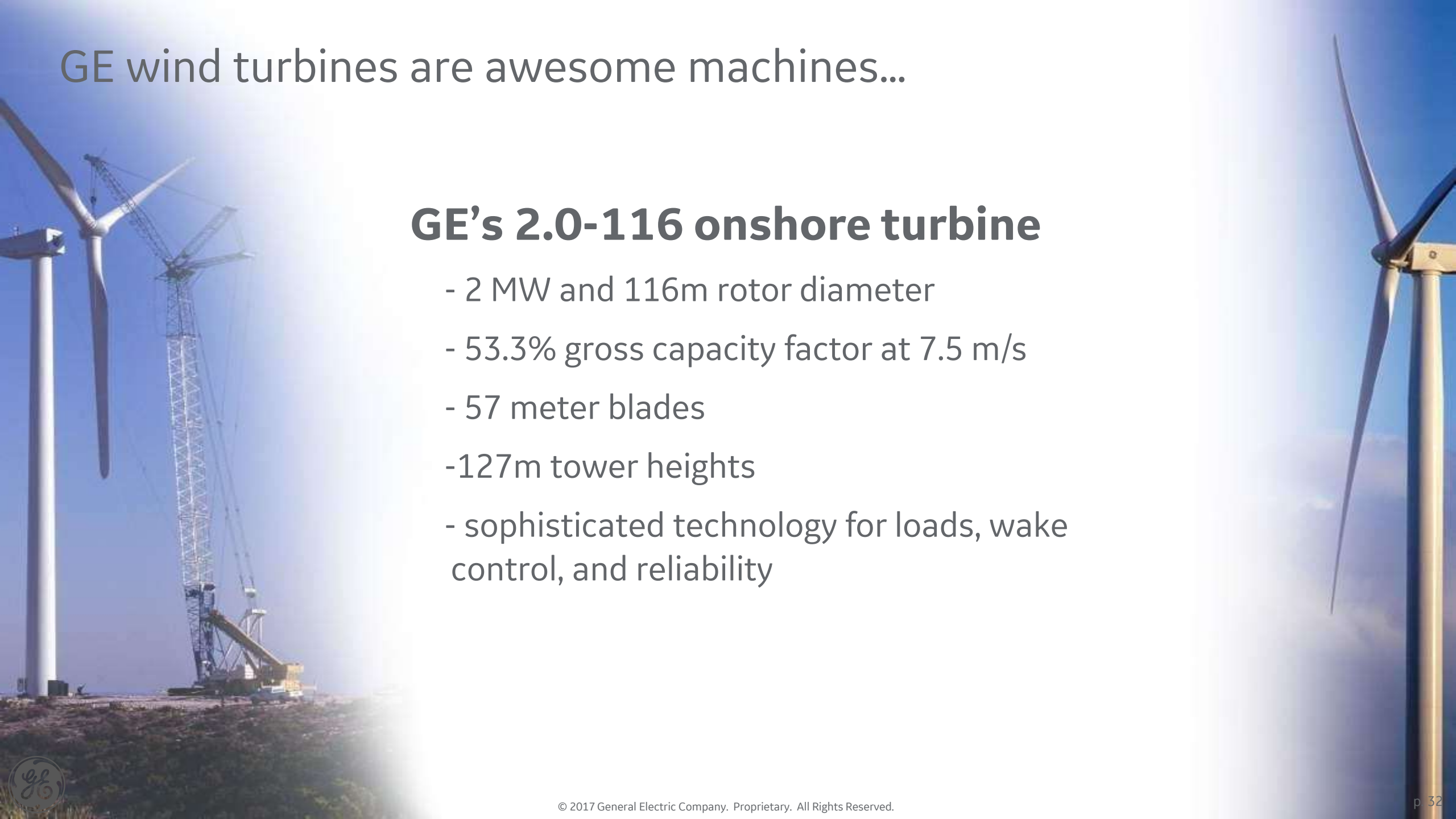
Collaborating with customers as
a leading player in the
hydropower market

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

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…and I love climbing them and spreading the word

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…and I thought you might enjoy a brief tour

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But they weren't always awesome:

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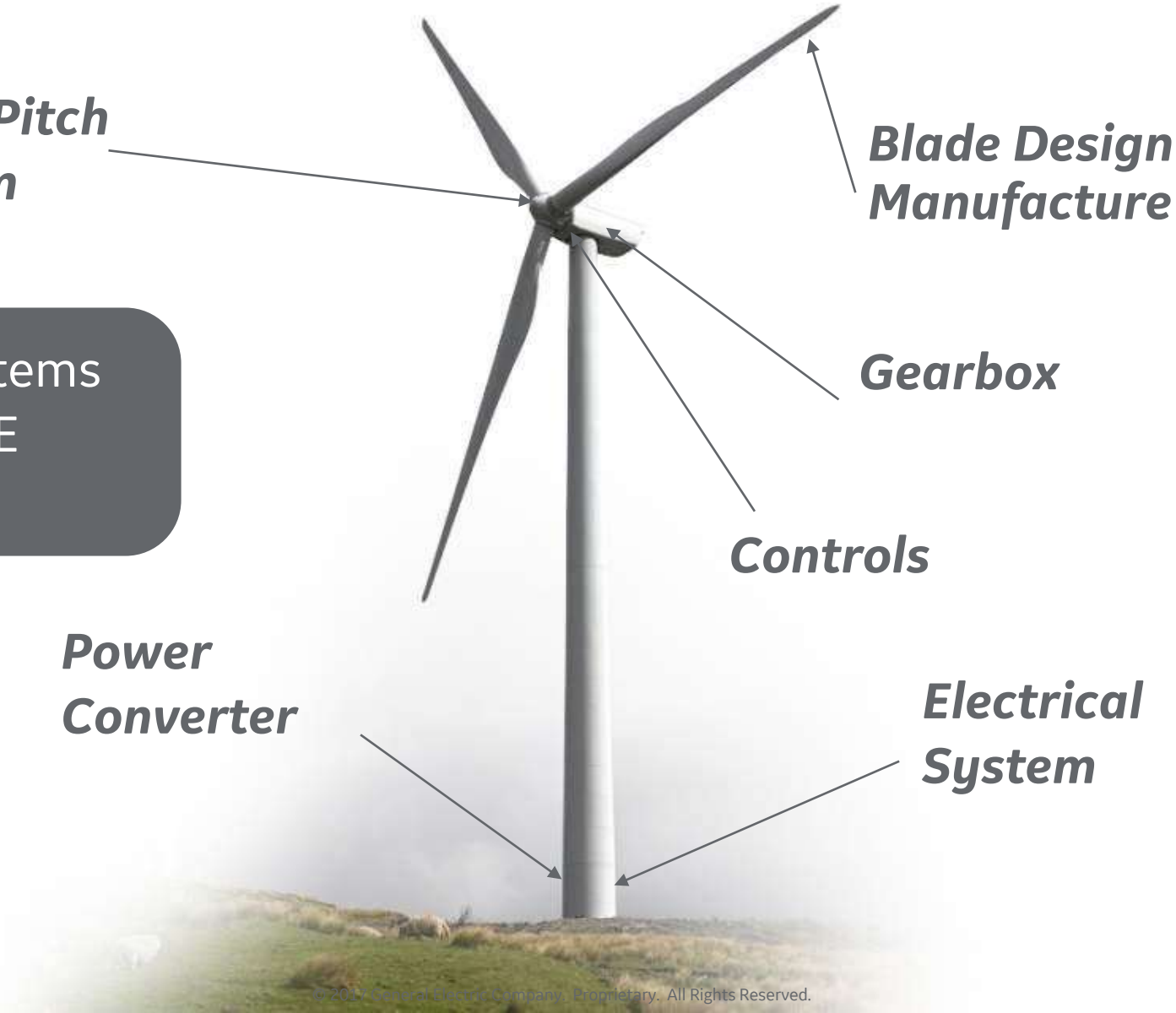
GE gradually replaced everything with our designs, internal manufacture

Redesigned systems introduce GE technology



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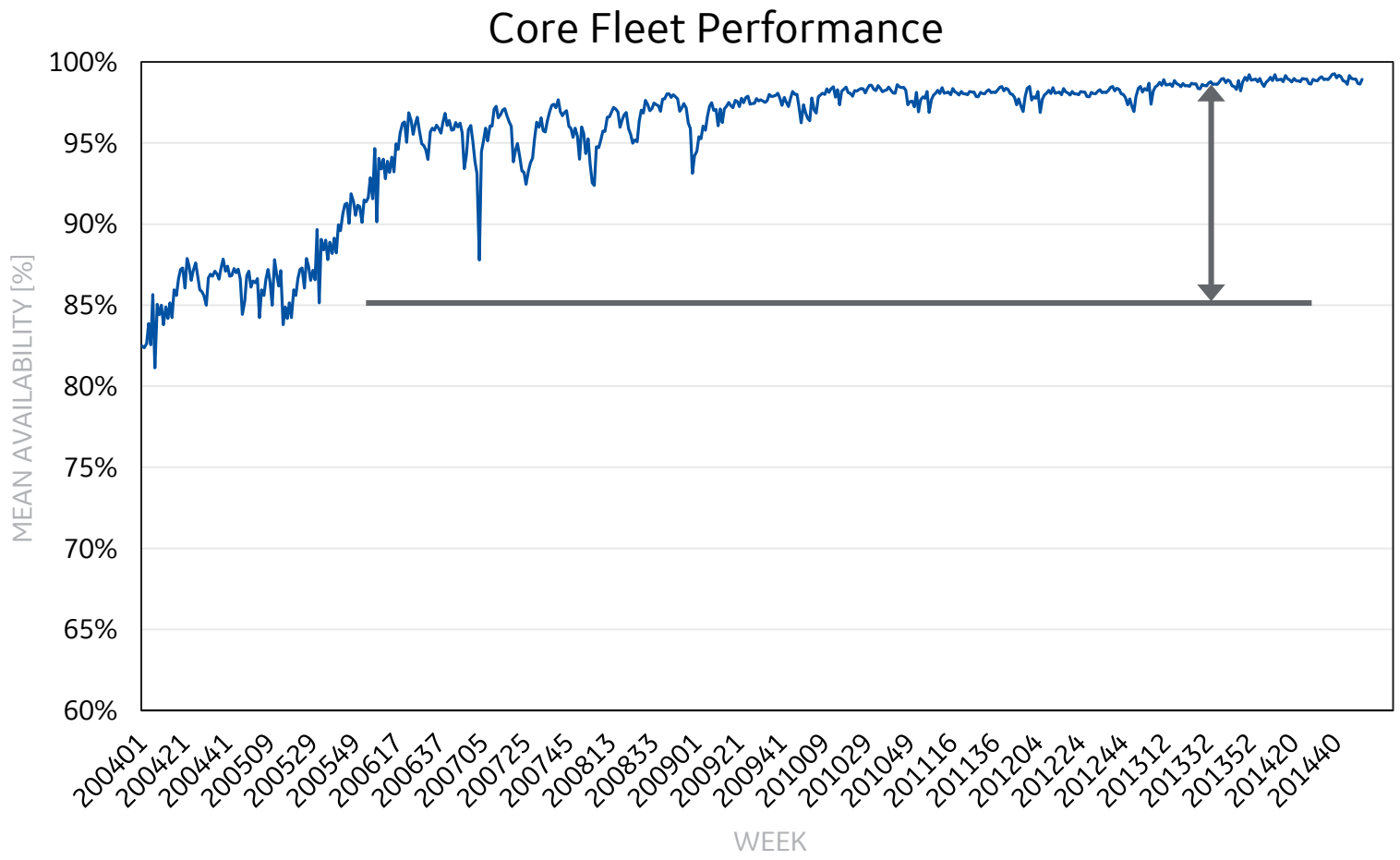
And the result was a huge increase in turbine availability



equal to output of 4,000 turbines

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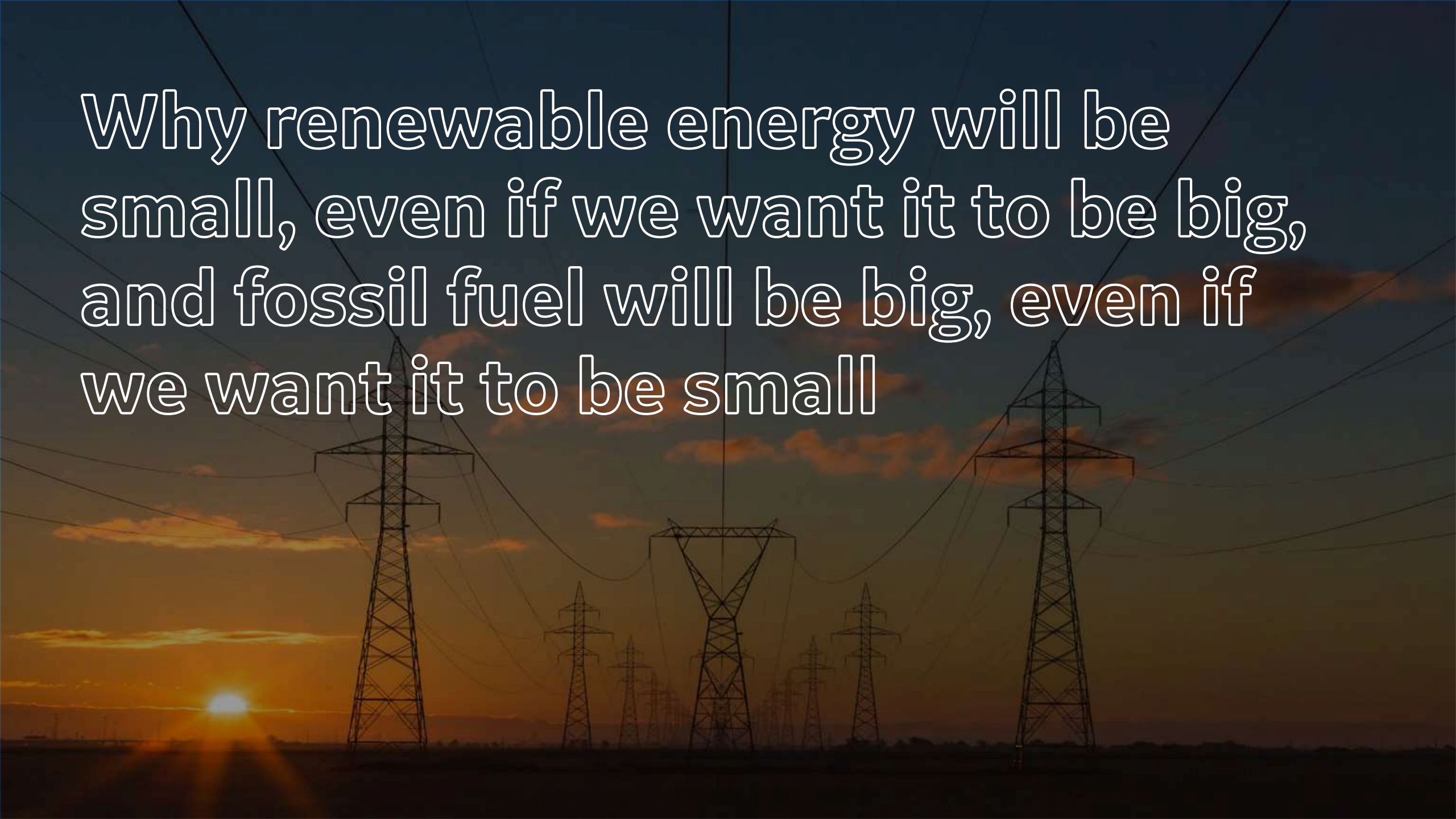
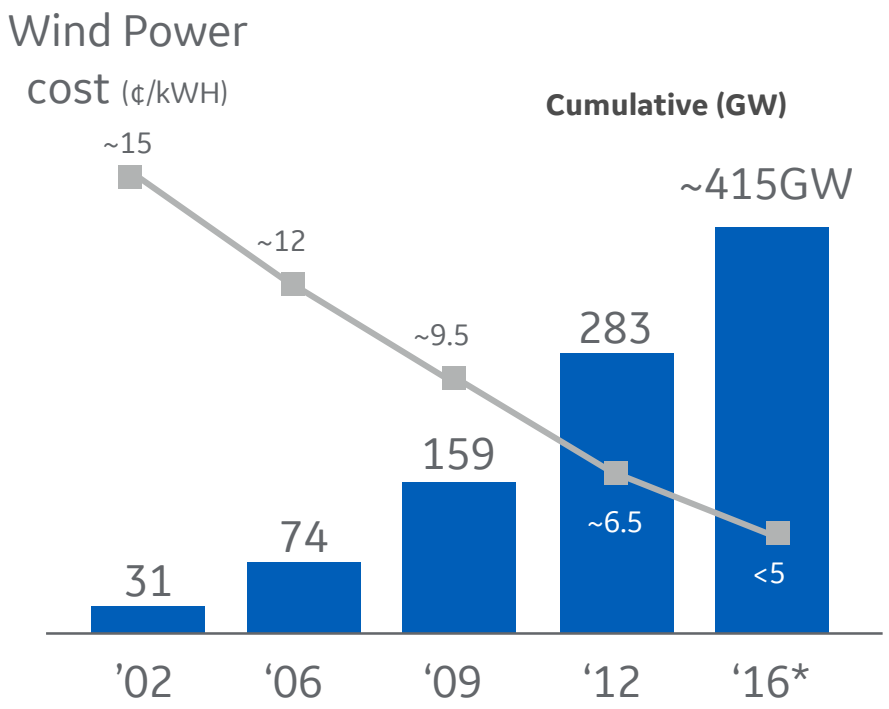
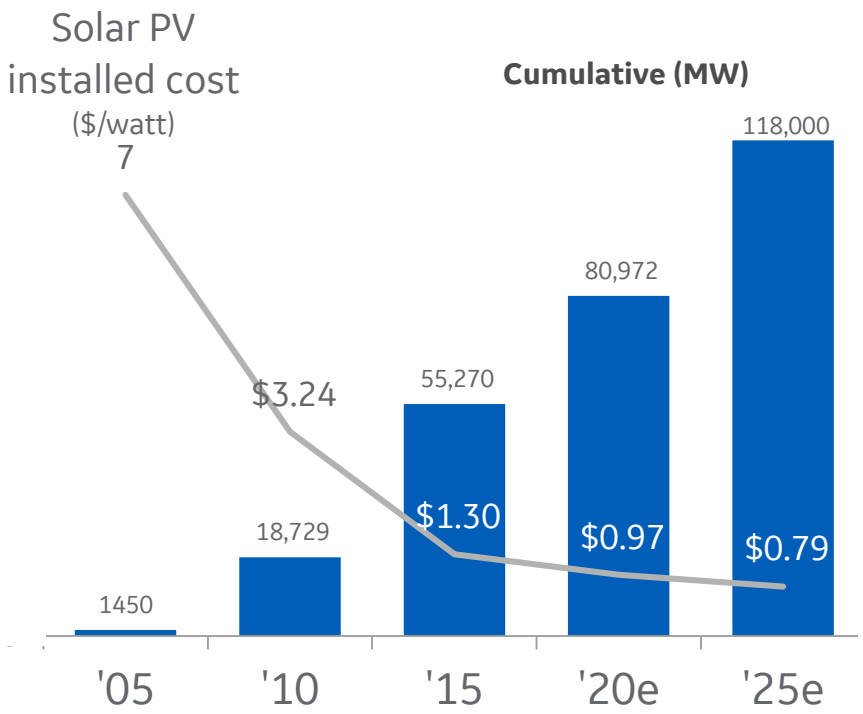

Why renewable energy will be small, even if we want it to be big, and fossil fuel will be big, even if we want it to be small

Wind and Solar costs keep dropping and installations keep growing





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And countries keep setting records for wind and solar output

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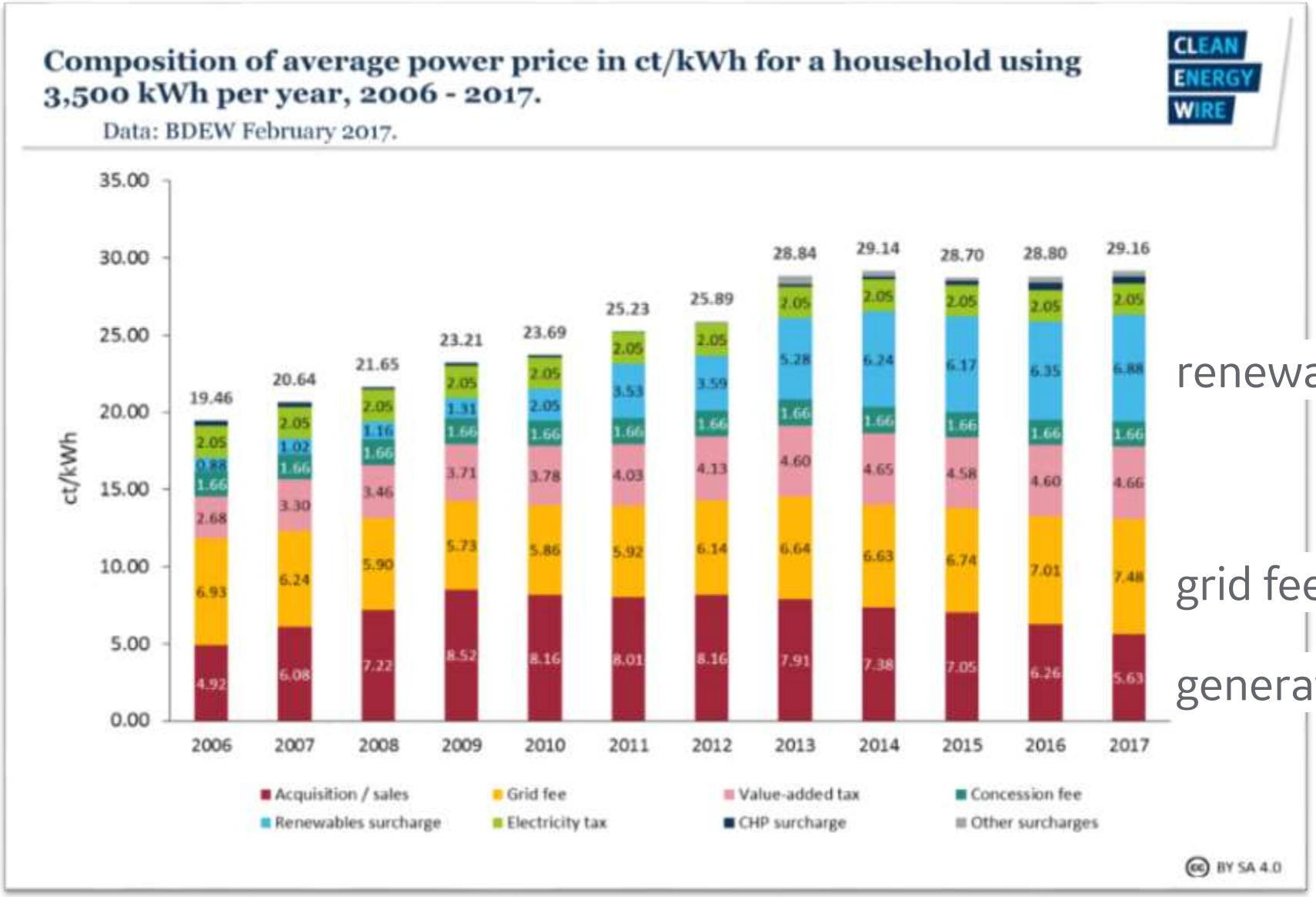
So why do electricity prices keep going up?



renewable fee

grid fee

generation fee

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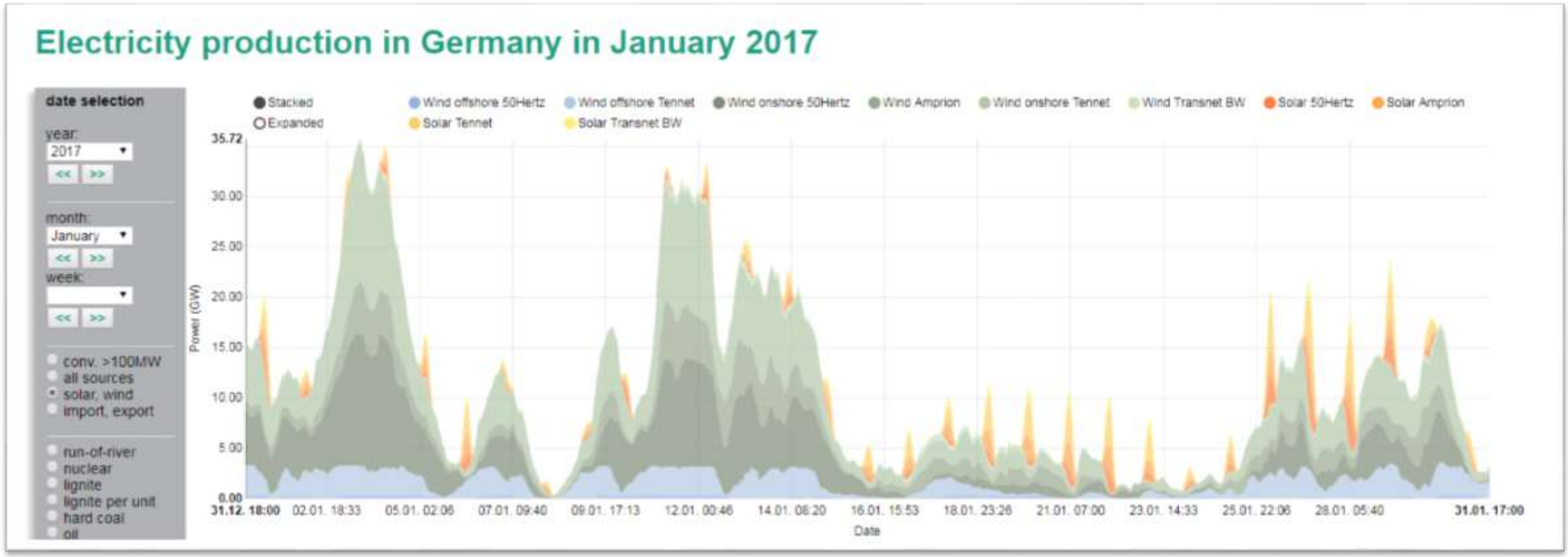
Renewables is *duplicate* capacity not *additional* capacity.



- What is the *minimum*, not the *maximum?*
- Conventional fuels are used less but everything still needed as backup.

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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

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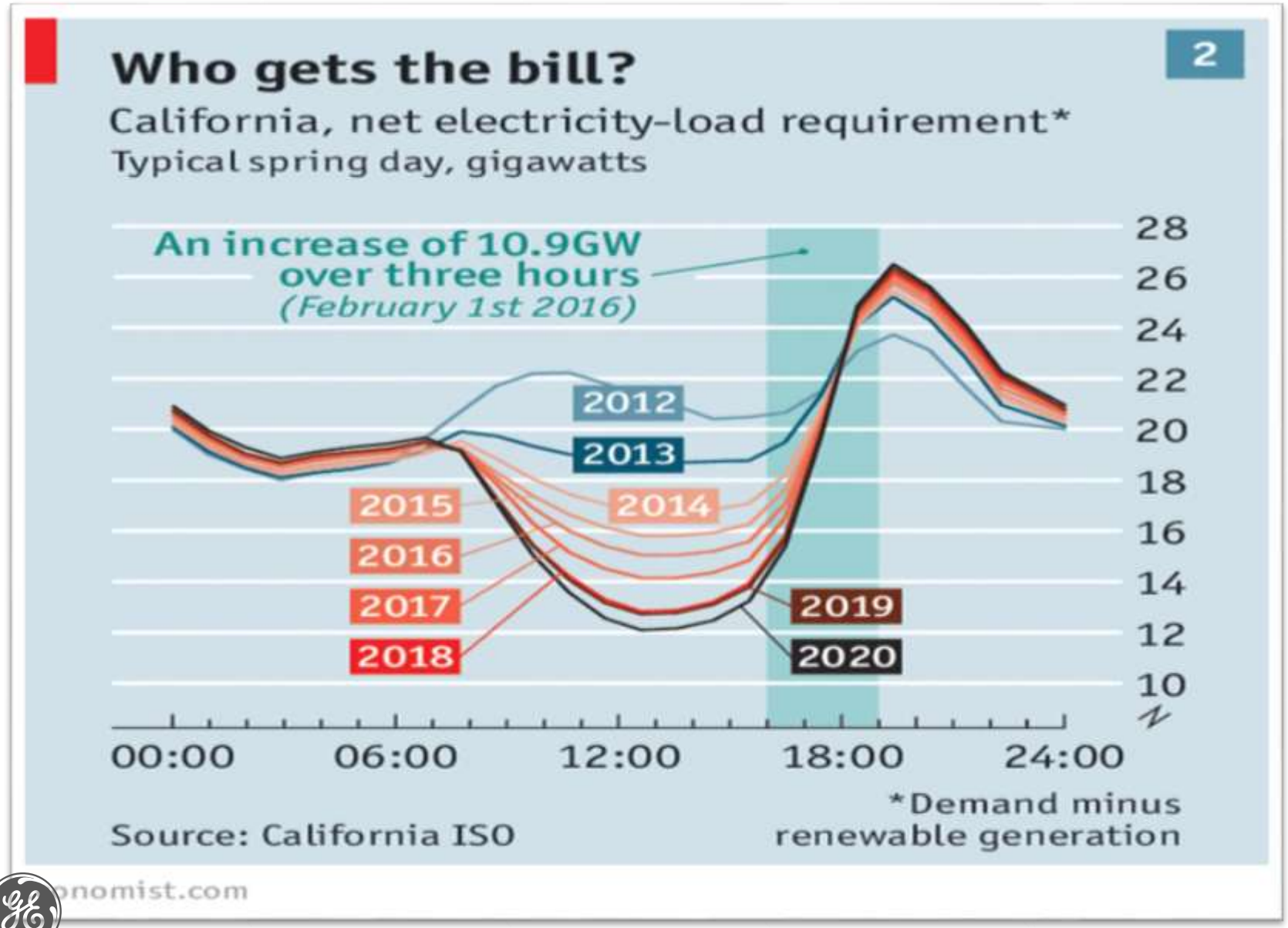
In addition, wind and solar put pressure on the grid....



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

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…and put pressure on conventional power producers

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

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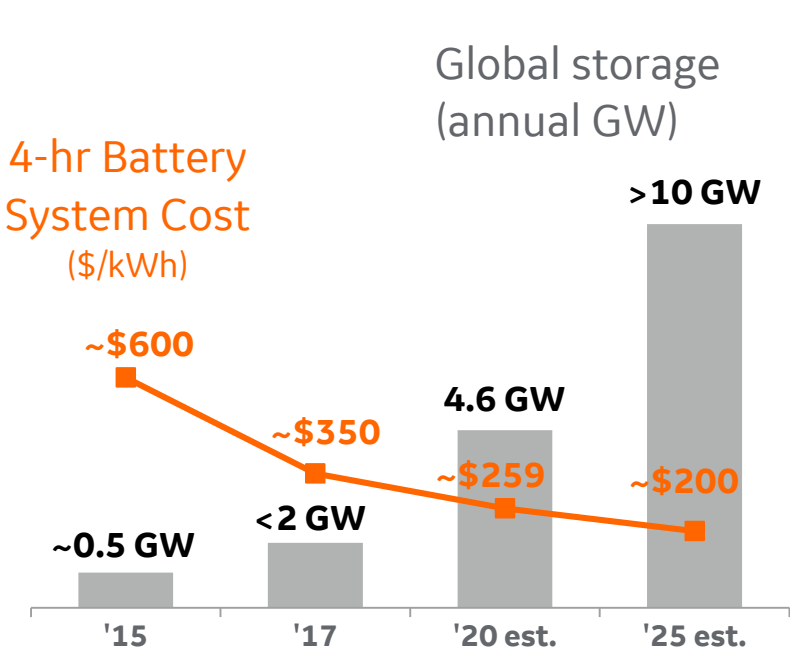
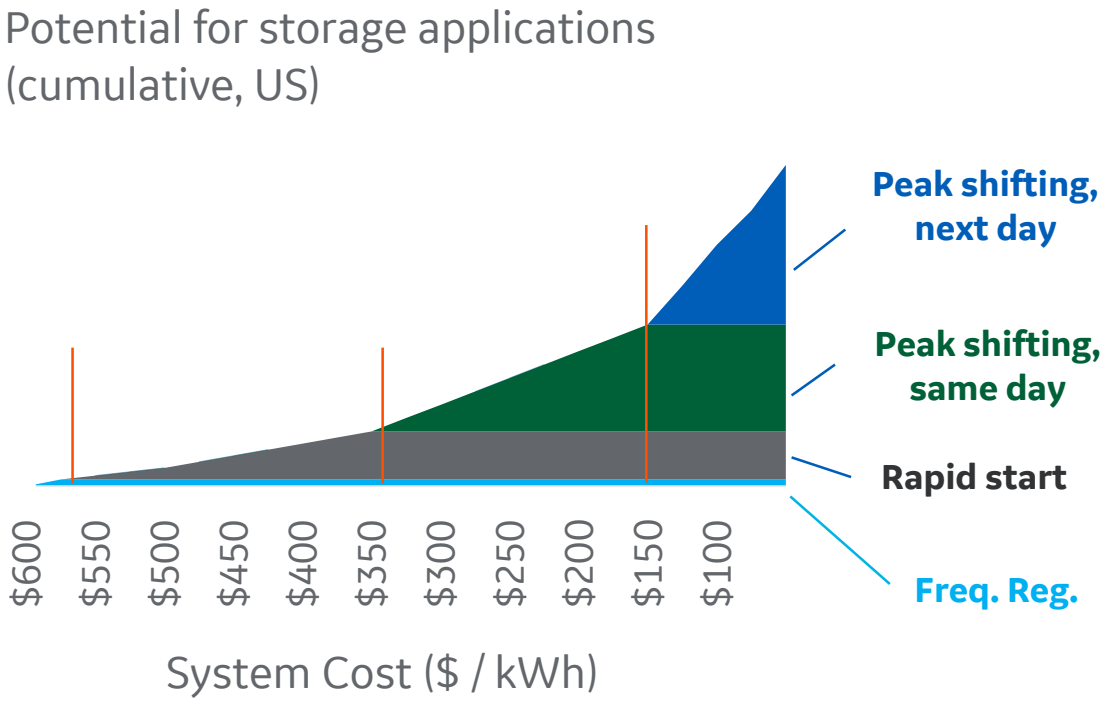
But what about storage?





As costs comes down, opportunities go up.

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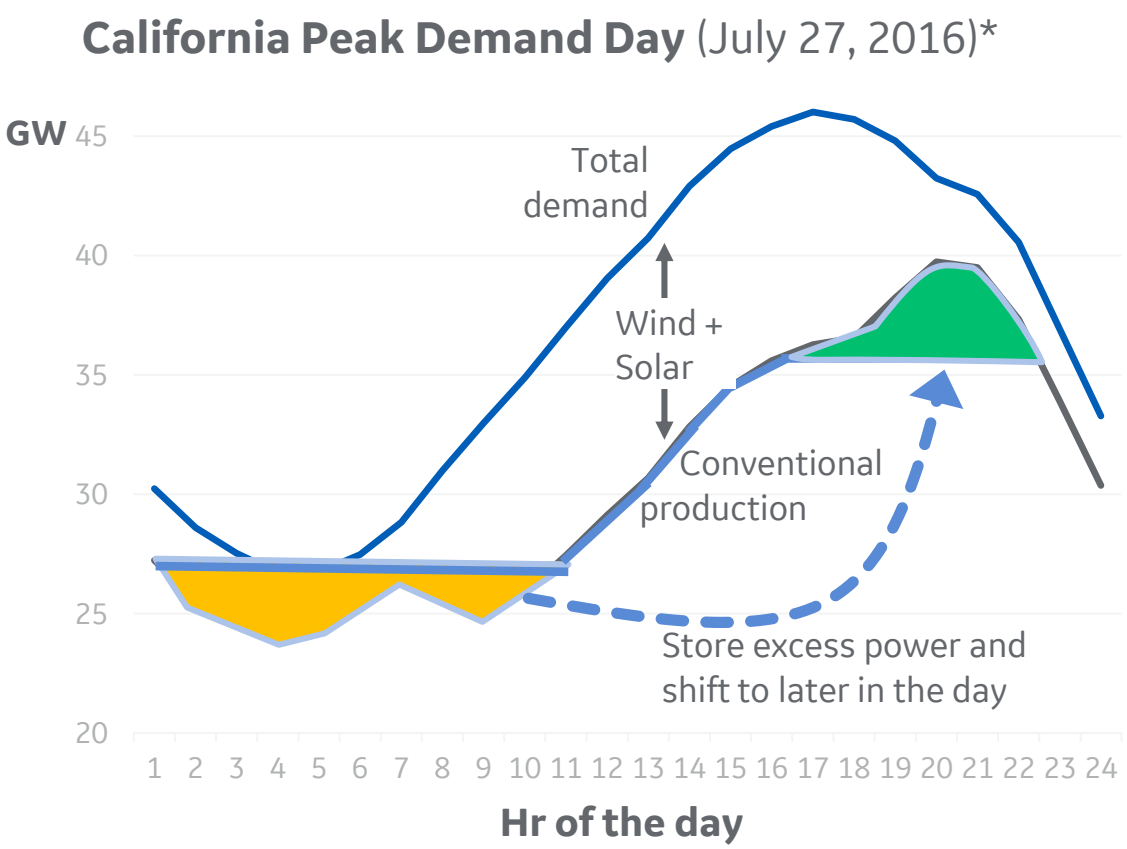
But even significant battery storage has a small impact on overall grid



* 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.

- 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%

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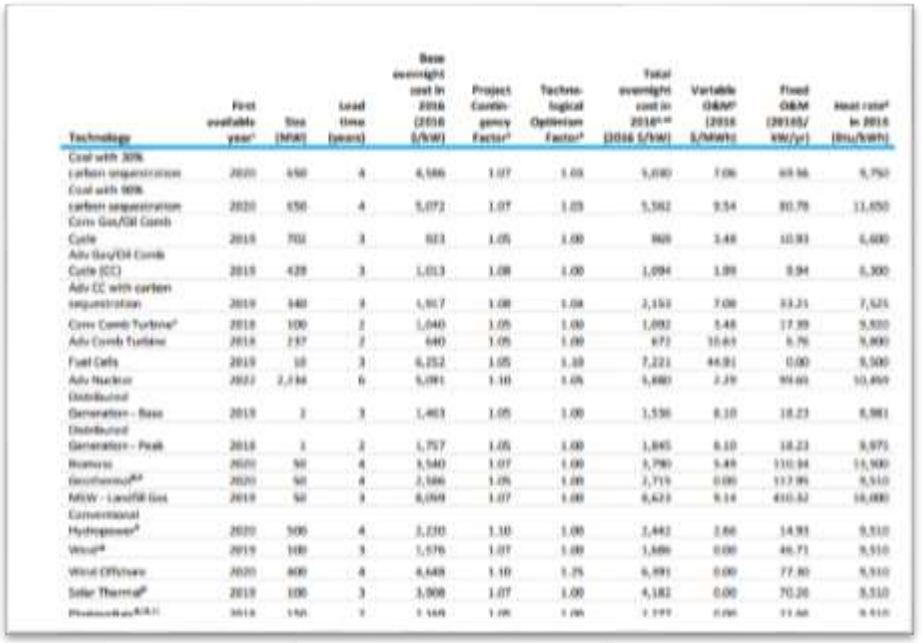
Renewables costs are getting competitive

Equipment and installation cost



Coal	$ 3,100 /kw
Nat gas	$ 970
Nuclear	$ 5,800
Wind	$ 1,700
Solar PV	$ 2,300

Operating cost

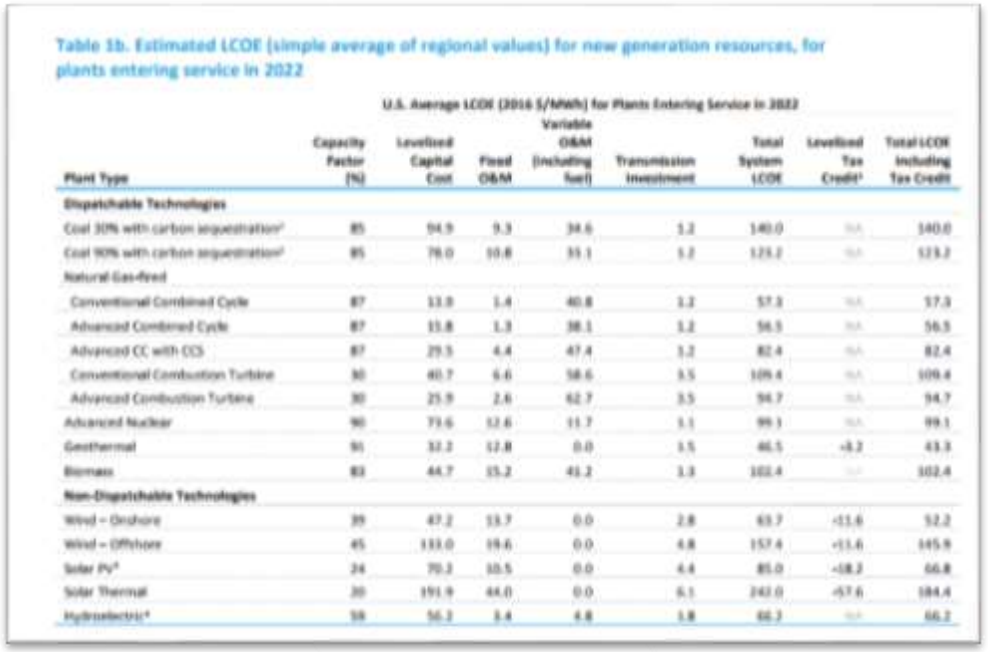


Table 1b. Estimated LCOE (simple average of regional values) for new generation resources, for plants entering service in 2022

U.S. Average LCOE (2016 $/MWh) for Plants Entering Service in 2022

Plant Type	Capacity Factor (%)	Levelized Capital Cost	Fixed O&M	Variable O&M (including fuel)	Transmission Investment	Total System LCOE	Levelized Tax Credit	Total LCOE including Tax Credit
Dispatchable Technologies								
Coal 30% with carbon sequestration	85	94.9	9.3	34.6	1.2	140.0	n/a	140.0
Coal 90% with carbon sequestration	85	78.0	10.8	33.1	1.2	123.2	n/a	123.2
Natural Gas-fired								
Conventional Combined Cycle	87	13.0	1.4	40.8	1.2	57.3	n/a	57.3
Advanced Combined Cycle	87	13.8	1.3	38.1	1.2	56.5	n/a	56.5
Advanced CC with CCS	87	29.5	4.4	47.4	1.2	82.4	n/a	82.4
Conventional Combustion Turbine	30	40.7	6.6	58.6	3.5	109.4	n/a	109.4
Advanced Combustion Turbine	30	25.9	2.6	62.7	3.5	94.7	n/a	94.7
Advanced Nuclear	90	73.6	12.6	11.7	1.1	99.1	n/a	99.1
Geothermal	91	32.2	12.8	0.0	1.5	46.5	-3.2	43.3
Biomass	83	44.7	15.2	41.2	1.3	102.4	n/a	102.4
Non-Dispatchable Technologies								
Wind – Onshore	39	47.2	13.7	0.0	2.8	63.7	-11.6	52.2
Wind – Offshore	45	133.0	19.6	0.0	4.8	157.4	-11.6	145.9
Solar PV	24	70.2	10.5	0.0	4.4	85.0	-18.2	66.8
Solar Thermal	20	191.9	44.0	0.0	6.1	242.0	-57.6	184.4
Hydroelectric	59	56.2	3.4	4.8	1.8	66.2	n/a	66.2

Coal	$ 35 /MWhr
Nat gas	$ 35
Nuclear	$ 20
Wind	$ 12
Solar PV	$ 9

But, again, is cheap intermittent power as good as expensive reliable power?

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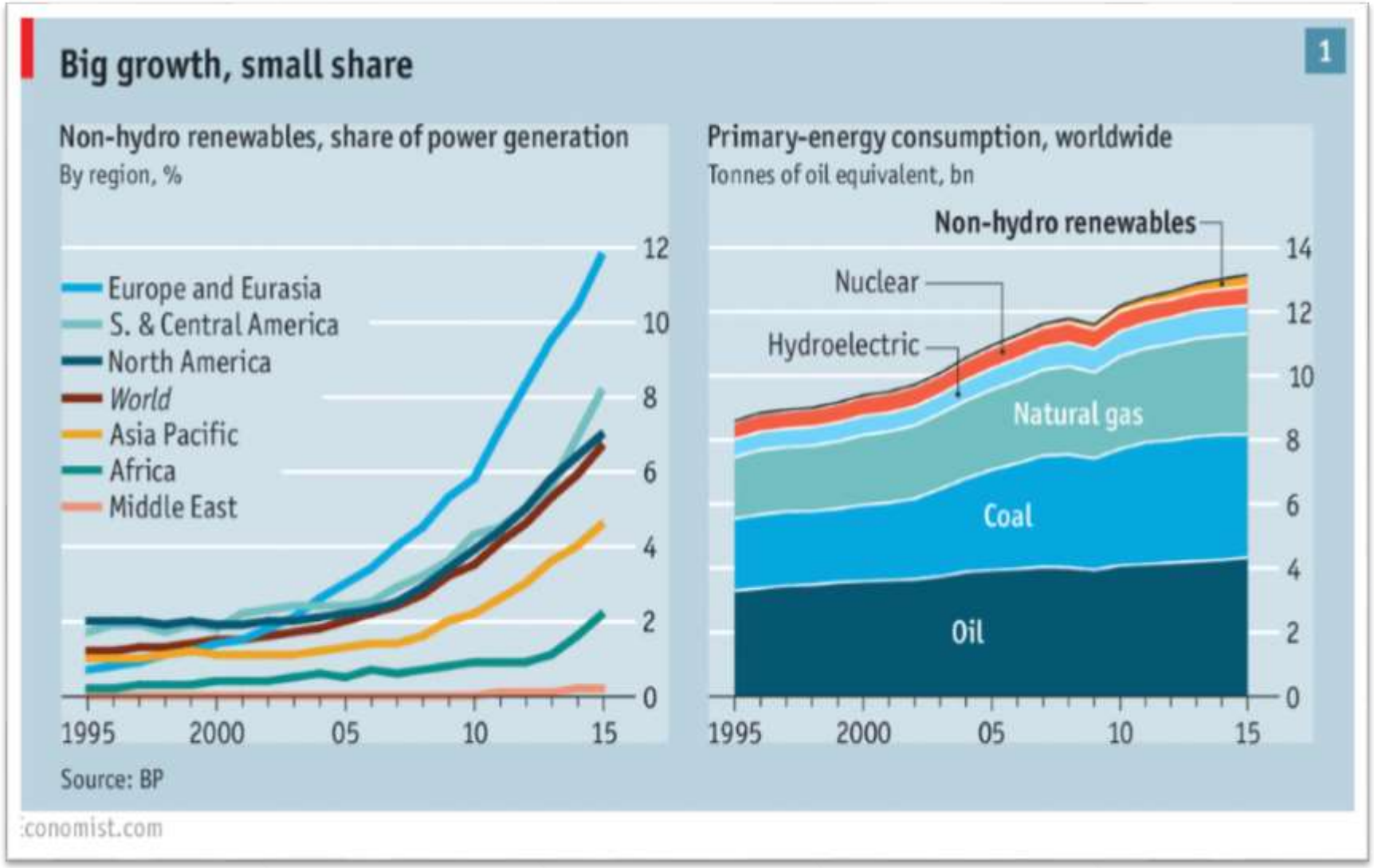
Consequently, renewables is growing fast but is a small slice of total pie



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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

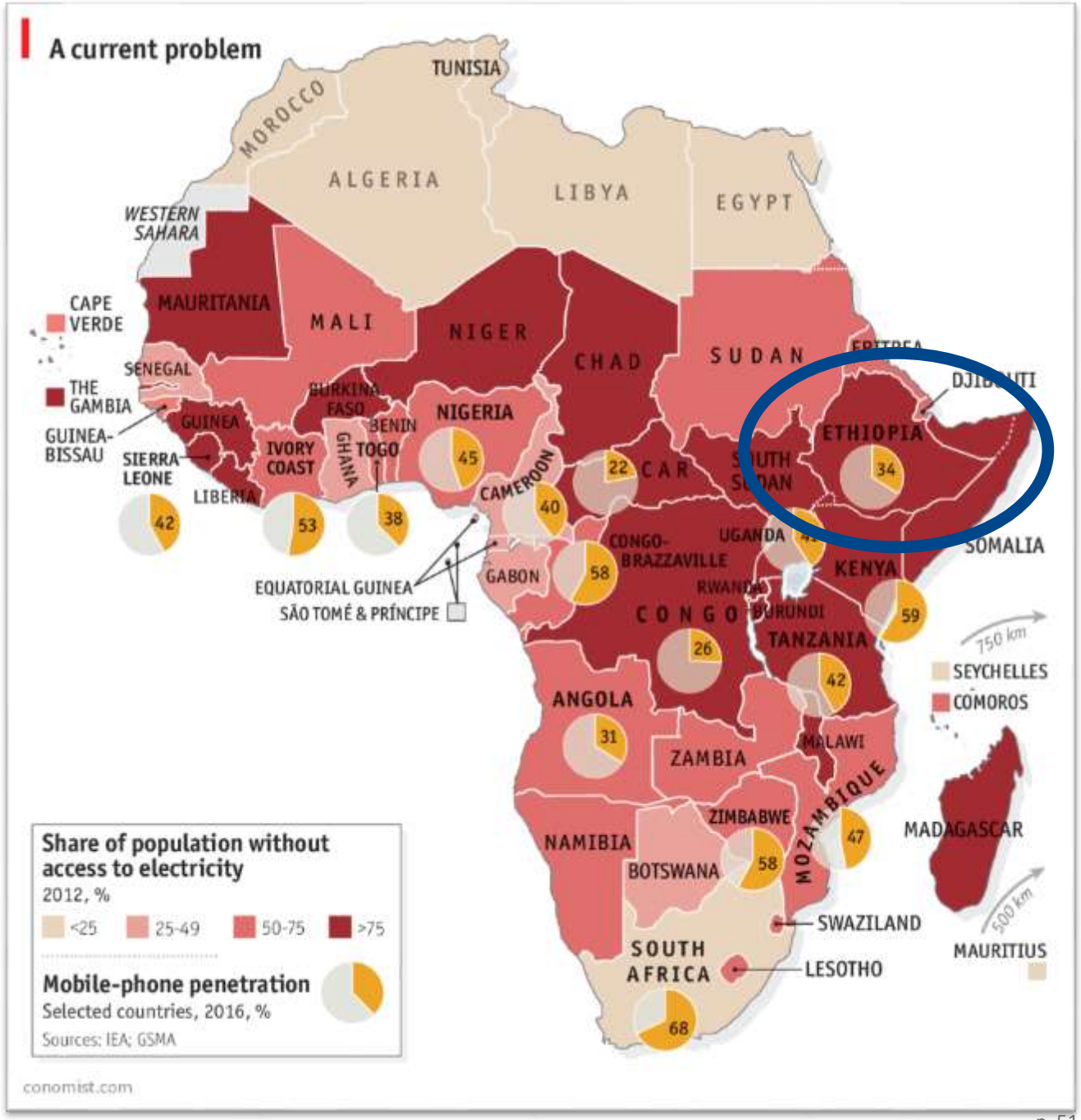
Africa

- 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



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Problem 2: Long term global impact

So, what would *you* do with $1B?

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

The answer is not obvious

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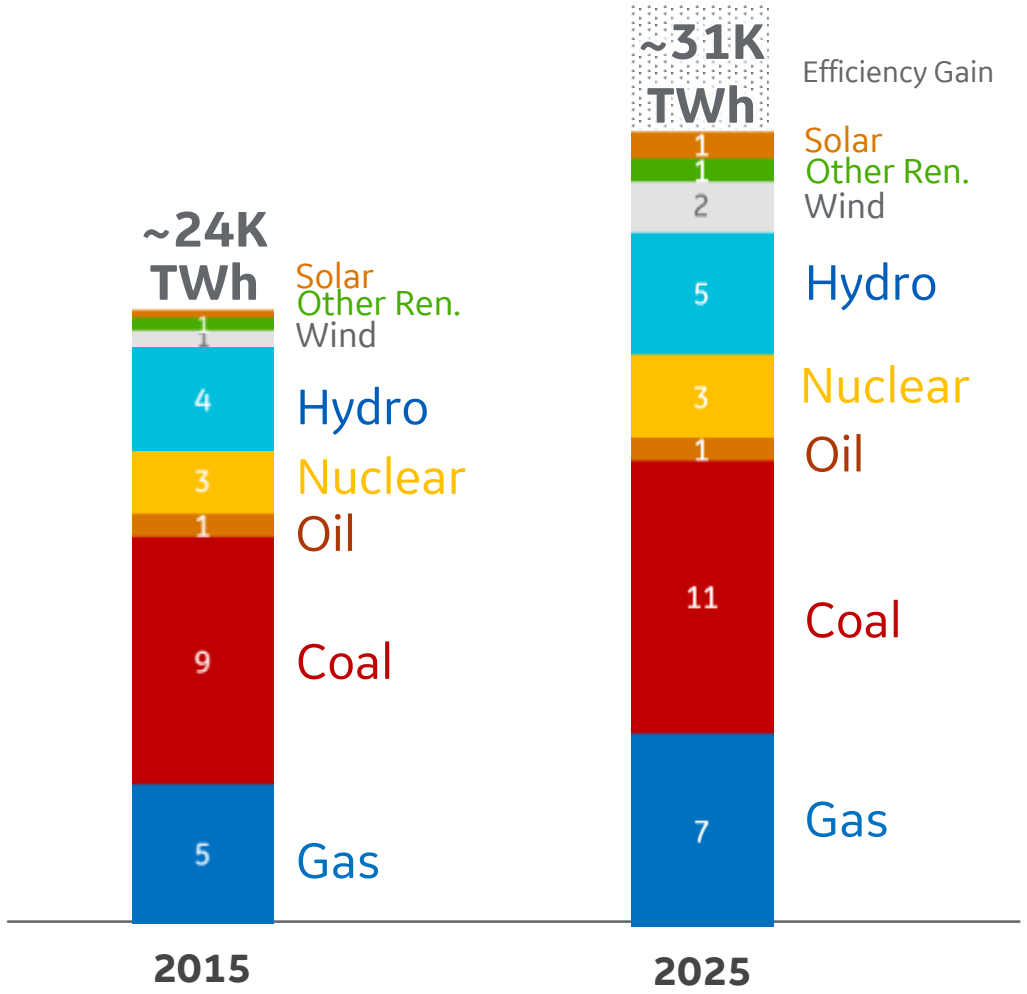
My guess is that the future will not be too different from the past

global electricity generation by fuel



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All this and more will be part of the solution.

AERO ENGINES

SOLAR PV

GAS TURBINES

ONSHORE WIND

GE HITACHI NUCLEAR

POWER CONVERSION

OFFSHORE WIND

STEAM TURBINES

PLANT EQUIPMENT

HYDRO

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

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Thank you