Power Plant Economics: Analysis Techniques & Data

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Outline

Analysis Techniques:

- Time value of money + Uniform payment series + Present value
  - Worked example of a power plant's lifetime financing
  - Application in computing a breakeven **Levelized Cost of Energy**: **LCOE**

Energy Information Agency data on LCOE: 2011 - 2018

- Analysis of EIA data peculiarities and trends
- Examining the EIA assumption of across-the-board 30 year power plant lifetime

LCOE data from Lazard and Bloomberg

Comparison of data from all sources

- Resulting conclusions about present day renewable energy economics

Appendix tables of "U/P", "P/U", "F/P" and "P/F" function values

(Written / Revised: March 2021)

Power Plant Economics: Analysis Techniques & Data

In his book, David MacKay chose to ignore the economics of power systems

- He wanted to teach about fundamental energy issues and challenges
- And feared that economics was a quagmire the reader might never escape

I have followed a similar strategy in my focus upon the **science** of power systems

But I cannot now walk away without discussing dollars and cents

- Yes, energy costs are changing all of the time!
- Yes, **real** (fully inclusive) costs can be hugely controversial!

But, in a capitalist system, costs **will** determine the future of our energy systems

Unless we now choose to **alter** that future via public policy

- In which case we'd better understand the real costs of **those** interventions

Figuring out the purchase price of a power plant:

It should be simple to find the cost of a power plant of **type X** and **capacity Y**

At least it should be simple for **well established** technologies

Such as coal, gas, hydro, or nuclear power plants

After all, we've already built **hundreds** or even **thousands** of these!

Further, these were mostly built by public and/or government-regulated companies

So that data, at least, should be readily available, right? WRONG!

Regulated or not, these companies keep their costs analyses **very** private!

And **this** is just the initial purchase price of the power plant!

To which labor, fuel and operating costs still need to be added

*Complete comparative data **are** generated in certain reports*

Most of which are published by governmental agencies

These agencies should be nominally unbiased about competing technologies

Possibly offset by their naiveté about certain new technologies

A point I will return to late in this lecture

And, now, they've become the target of political intervention & censorship

Their reports state costs in strange ways, using strange terms such as

Net Present Value OR **Overnight Capital Cost** OR **O&M Cost**

OR, most importantly, whole categories of **Levelized Cost**

To make sense of these terms and data, we need to learn a bit of . . .

"Engineering Economics"

Concept #1 - **The Time Value of Money**:

Which encapsulates the investor's view of what his/her money is really worth

Present value = P = How much money that investor has right now

Future value = F = What investor expects that money to be worth in the future

Which will be greater, because investor expects money to **earn interest**

To be paid by whomever he/she loans/invests that money to/with

F = P + cumulative interest earnings up to that future date

If annual interest rate is **i**, the future value of that money will become:

Future value at end of year 1 = $P\,(1 + i)$

Future value at end of year 2 = $[P\,(1 + i)](1+i)$

Future value at end year n: $\mathbf{F(at\ n) = P(1+i)^n}$ **(1)**

Engineering Economics continued:

Concept #2 - **Uniform Series Payment**:

Which addresses the repayment of a loan, or income from a loan/investment

Common way distributing repayments is by **uniform** amount repaid each interval

Where interval may be once a year, or once a month

Which is exactly what you do with a home mortgage or auto loan

We will work out this series by computing payments, interval by interval

Accounting for investor's expectation of interest income

That income is usually expressed as an annual percentage interest rate ("APR")

Whereas payment intervals are usually months

in which case interest per month can be taken as = APR / 12

Working out a uniform series of payments:

Assume a payment of U each payment interval (on a loan/investment of P):

Working out entries for the **END** of each payment interval:

Interval:	Owed:	Paid:	Then owed (= Owed – Paid)
1	$P(1+i)$	U	$P(1+i) - U$
2	$[P(1+i) - U](1+i)$	U	$[P(1+i) - U](1+i) - U$
3	$\{P(1+i) - U](1+i) - U\}(1+i)$	U	$\{P(1+i) - U](1+i) - U\}(1+i) - U$
n			$P(1+i)^n - U \Sigma_{j=0}^{\text{to } n} (1+i)^j$

Now say that U is chosen such that loan is to be paid off at that n^{th} payment:

So "Then owed" must then be zero => $P(1+i)^n = U \Sigma_{j=0}^{\text{to } n} (1+i)^j$

Which, after some clever algebra, gives: **$U = P \{ i / [1 - (1+i)^{-n}] \}$** **(2)**

Playing a bit with these two relationships:

First relationship converted present value (of money) into its value at a future date

Future value (after n time intervals) = Present Value $(1+i)^n$ OR:

$F/P\ (i, n) = (1+i)^n$ where "F/P" is the name of the conversion function

Reverse conversion function is then **$P/F\ (i, n) = (1+i)^{-n}$**

Second relationship took present value (of loan) and converted to series of payments

Uniform Payments (over n time intervals) = Loan $\{ i / [1 – (1+i)^{-n}] \}$ OR:

$U/P\ (i, n) = i / [1 – (1+i)^{-n}]$ where "U/P" is name of conversion function

Reverse conversion function is then **$P/U\ (i, n) = [1 – (1+i)^{-n}] / i$**

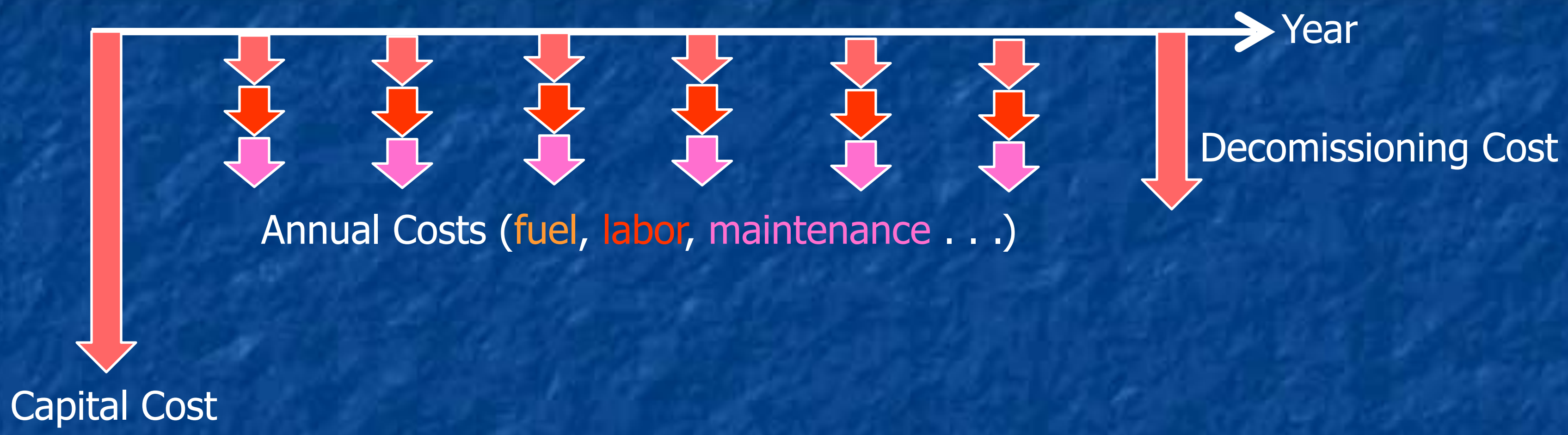
Expressing these as conversion functions can do two things:

Help you remember/see what a given calculation is really doing AND

Save computing because they're in textbooks (and at end of this lecture)!

Let's now apply this to compute a **Levelized Cost***:*

Over power plant lifetime, there will be series of expenses => **Cash Flow Diagram**



To figure out the price charged for power, we need to know "Levelized Cost" per year

Computation requires two steps, each answering a question:

1) "How much money would I need **up front** to **eventually** meet those expenses?"

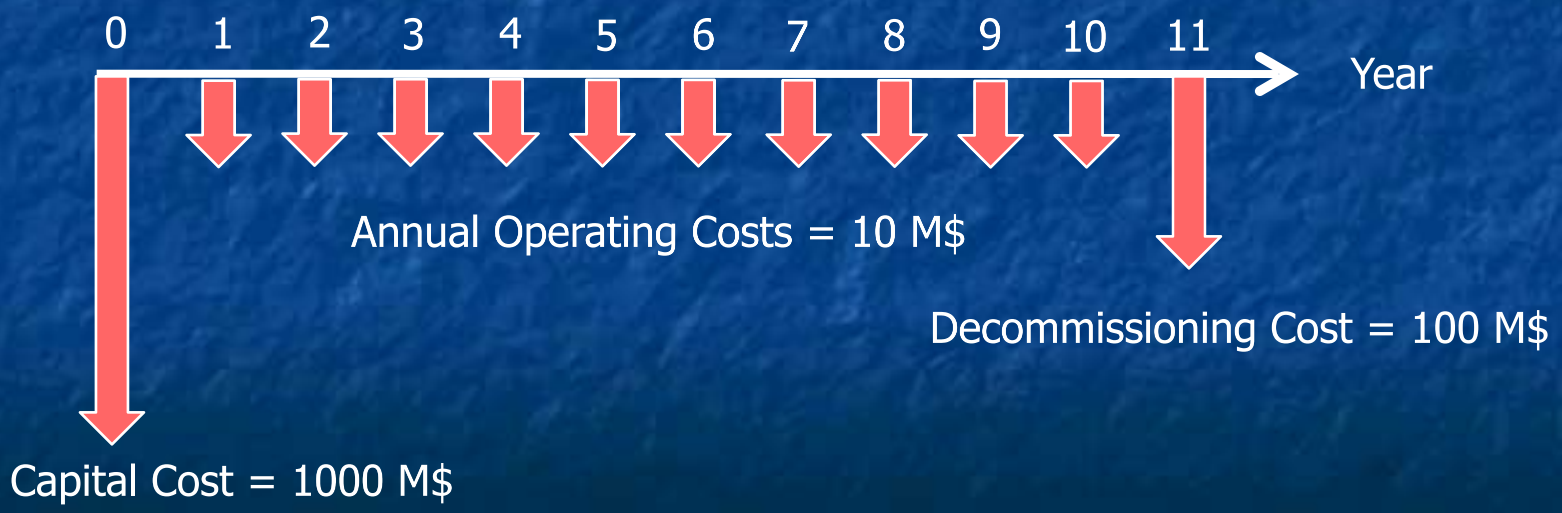
2) "If you loaned me that money now, what would I need to pay back each year?"

Choosing some values for our power plant calculation:

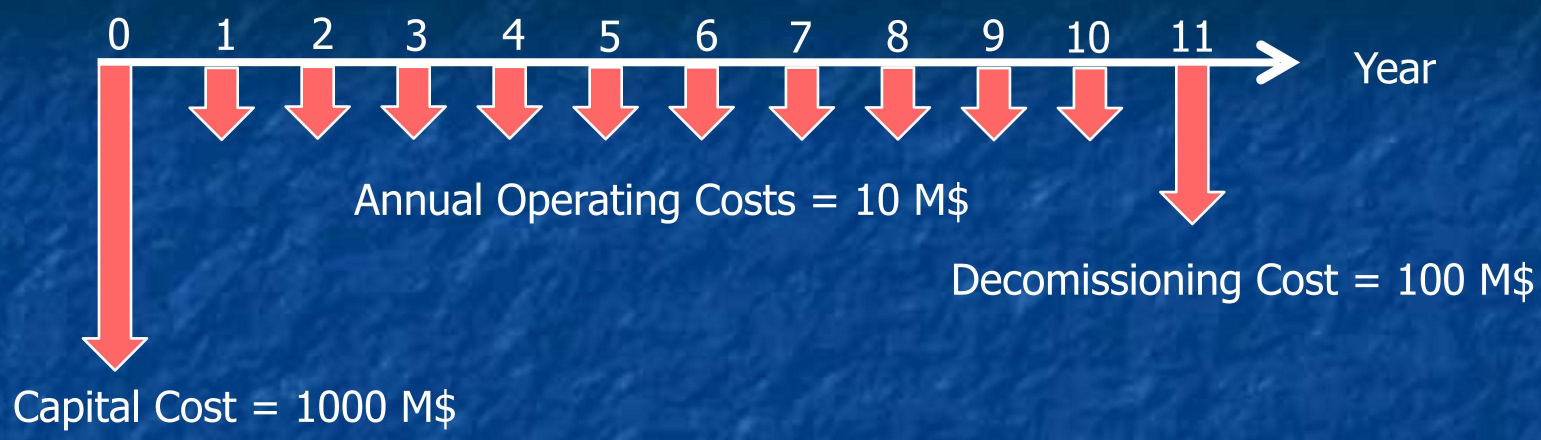
Our hypothetical power plant, to be financed with a 10% annual interest loan:

Capital cost:	1000 M$
Operating lifetime:	10 years
Annual costs (inaccurately lumped together):	10 M$
Decommissioning cost	100 M$

Inaccurately assuming plant is built overnight and decommissioned in 1.0 years:



Step 1) Money needed up front = **Present Values** *of all costs:*



a) **Present Value of Capital Cost:** **$P_{capital}$ = 1000 M$**

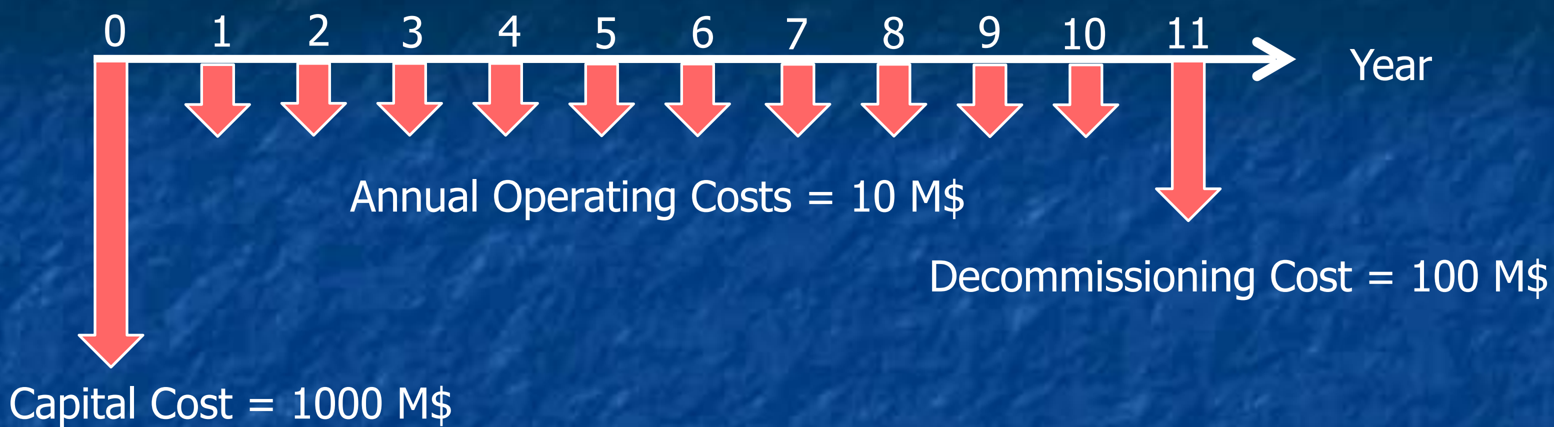
No conversion is necessary! Because it's a cost right now, at time = 0

b) **Present Value of Decomissioning Cost comes from its Future Value:**

Conversion function is P/F (10%, 11 yrs) = $1 / (1+0.10)^{11}$ = 0.3504 =>

$P_{decomissioning}$ = 100 M$ x P/F (10%, 11 yrs) = 35.04 M$

Plus Present Value of all those annual costs:



c) **Present Value of Annual Operating Costs:**

String of payments ~ Uniform Payment Series with U = 10 M$

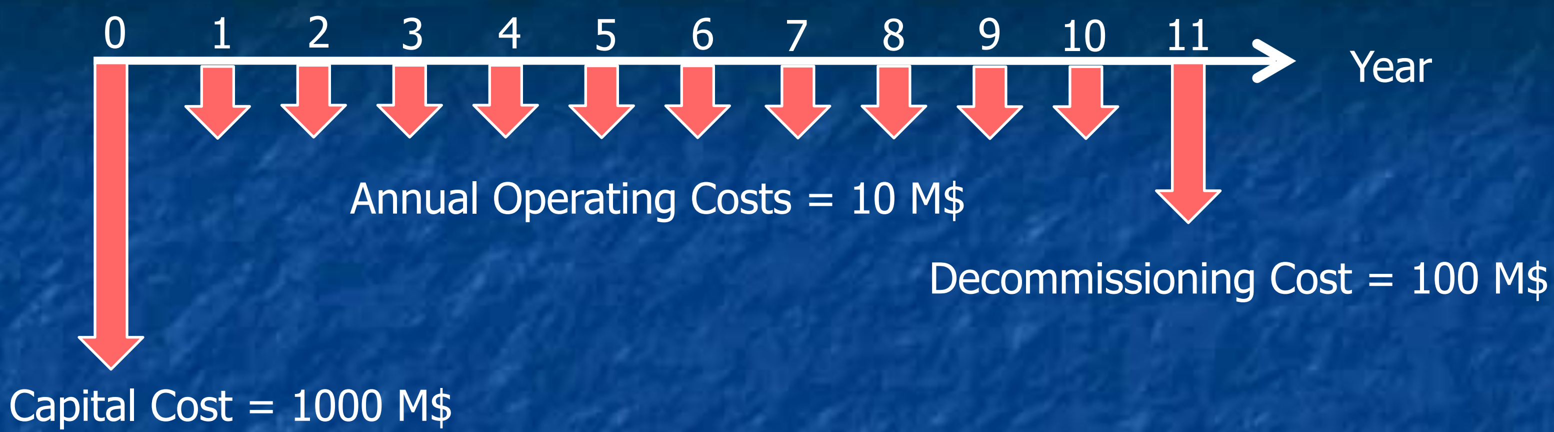
Convert this to the Present Value (of the corresponding loan/investment) with:

P/U (i=10% = 0.1, n=10 yrs) = $[1 - (1+0.1)^{-10}] / 0.01$

From textbook (or my tables at end of this lecture) P/U (10 yrs, 10%) = 6.1446,

$P_{\text{operating costs}}$ = 10 M$ x P/U (10%, 10 yrs) = 61.446 M$

Completed "Net Present Value" calculation:



Net Present Value of the above total cash flow = Sum of present values:

NPV $= P_{\text{capital cost}} + P_{\text{operating costs}} + P_{\text{decommissioning costs}}$

= 1000 M$ + 10 M$ P/U (10%, 10yrs) + 100 M$ P/F (10%, 11 yrs)

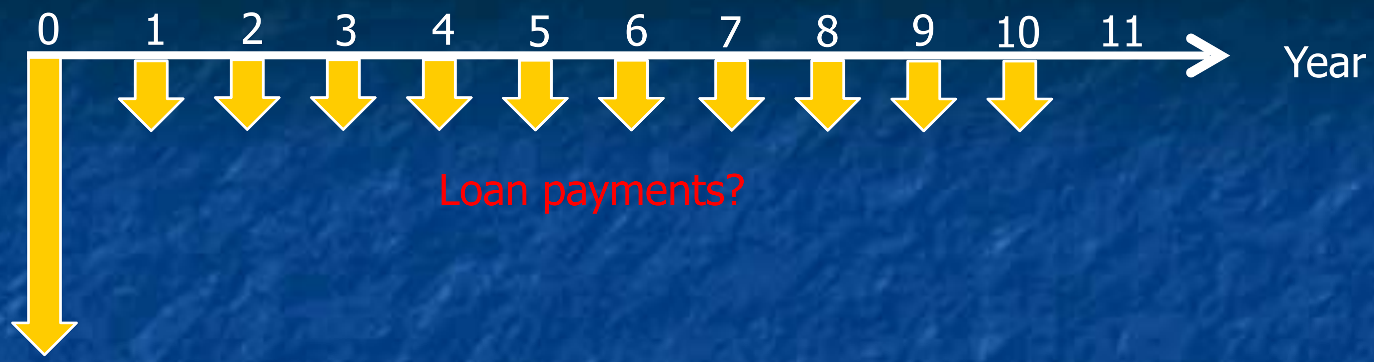
= 1000 M$ + 10 M$ (6.1446) + 100 M$ (0.3504)

= 1000 M$ + 61.44 M$ + 35.04 M$ = **1096.48 M$**

Compare this to simple sum of costs (which ignores the "time value of money"):

Simple Sum of Costs = 1000 M$ + 10 x 10 M$ + 100 M$ = 1200 M$

Step 2) Annual cost of loan to cover that up front cost



Up front cost = NPV = 1096.48 M$

Uniform Payment Series of payments you'd now have to pay for n years:

$U = P \{ i / [1 - (1+i)^{-n}] \}$ => NPV x U/P (n, i)

For a 10 year loan at the same 10% interest rate:

U = 1096.48 M$ x U/P (10%, 10 yrs) = 1096.48 M$ x (0.1627)

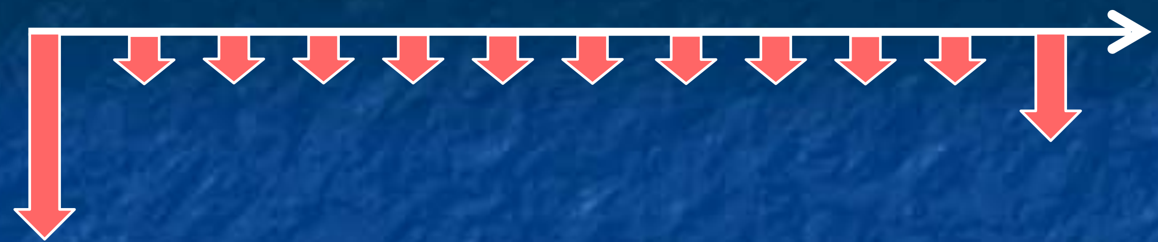
= **178.39 M$ / year** (totaling 1783 million over the life of the mortgage)

THIS is money you have to recoup through your annual power sales

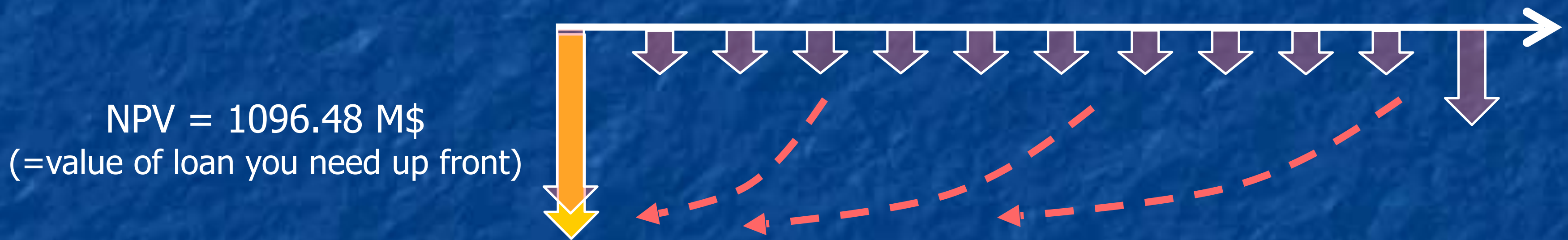
Divided by plant's annual energy output => LEVELIZED COST OF ENERGY

*Schematic of entire **Levelized Cost of Energy (LCOE)** calculation:*

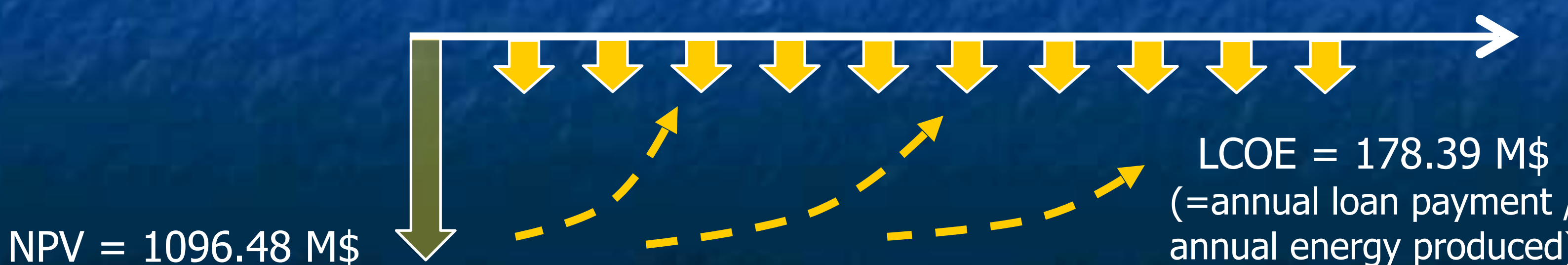
Start with Cash Flow:



Convert all costs to **Present Values**, adding to get **Net Present Value**



Convert NPV to corresponding **Uniform Series Payment => Levelized Cost**



Hold it, why not just pay annual costs from annual income?

1) Get a loan to cover ONLY THE CAPITAL COST of plant (10 year / 1000 M$ loan):

Payment, each year, on that loan:

$U_{capital}$ = U/P (10 year, 10%) x 1000 M$ = (0.1627) x 1000 M$ = 162.7 M$

2) Plus, each year, put away part of annual income to cover decommissioning cost:

$U_{decommissioning}$ = U/P (10 year, 10%) x 100 M$ = (0.1627) x 100 M$ = 16.27 M$

3) Plus, each year, pay your operating costs (in real time) of 10 M$

Giving you a total annual cost of: 162.7 + 16.27 + 10 M$ = **193.97 / year**

Versus previous LCOE financing scheme of **178.39 M$ / year**

Strange backward / forward LCOE financing scheme DOES make sense!

Where can we find levelized costs of energy?

From the **U.S. Energy Information Administration** ("EIA") which issues:

A yearly: **Annual Energy Outlook**

With sub-report: **Levelized Cost of New Generation Resources**

The latter sub-reports are particularly relevant to this lecture

I've found (and downloaded) these sub-reports for 2011 to present

They support the "**Outlook**" by estimating costs of power plants **initiated today**

Which, given licensing and construction times, take **years** to build

So **this year's** report is for new power plants coming on line **5 years from now**

And, as focus of these reports is on economics (and not on technology),

all costs given are LEVELIZED COSTS,

using the same methodologies that we covered above

*The 2018 EIA breakdown of **levelized** costs for different power plants:*

By fuel/variable costs, fixed operating costs, capital costs, transmission investment

2018 - US EIA - Levelized Cost of New Generation Resources in the Annual Energy Outlook

	Conventional Coal	Advanced Coal (IGCC)	Sequestered Coal (IGCC)	Natural Gas - Simple Turbine (CT)	Natural Gas (CC)	Sequestered Natural Gas (CC+S)	Hydroelectric	Nuclear	Wind - Onshore	Wind - Offshore	Geothermal	Biomass	Solar Photovoltaic	Solar Thermal
Costs in $ / MW-hr:														
Total Cost			119.1	85.1	50.1	74.9	61.7	92.6	59.1	138.0	44.6	95.3	63.2	165.1
Fuel + Variable Costs			38.5	55.7	34.9	42.5	1.8	9.3	0.0	0.0	0.0	39.6	0.00	0.0
Fixed Operating Costs			11.0	2.6	1.5	4.4	9.8	12.9	13.4	19.9	13.2	15.4	8.70	32.6
Capital Cost			68.5	23.6	12.6	26.9	56.2	69.4	43.1	115.8	30.2	39.2	51.2	128.4
Transmission Investment			1.1	3.5	1.1	1.1	1.9	1.0	2.5	2.3	1.4	1.1	3.30	4.10
Capacity Factor			85%	30%	87%	87%	64%	90%	41%	45%	90%	83%	29%	25%

RED = Notably poor values

GREEN = Notably good values

Tables = My Excel transcription from specified EIA report – Reports are available on my Resources Webpage

*Analyzing contributors to EIA total **levelized** cost, line by line:*

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Capacity Factor			85%	30%	87%	87%	64%	90%	41%	45%	90%	83%	29%	25%

Fuel & Variable Operating Costs (costs varying with the plant's output):

"Renewables" have zero to low fuel + variable costs because nature provides the fuel

EXCEPT for BIOMASS which does rack up substantial total fuel cost

Because farmers aren't dumb, they're going to **charge** for their garbage!

Fixed operating costs:

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Fixed Operating Costs:

- Solar Thermal has unusually high fixed operating costs
  - Likely due to the complexity of servicing and maintaining
    - 1000's of steerable mirrors ("heliostats") + boiler + turbine + generator

Transmission investment and Capacity factors:

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Capacity Factor			85%	30%	87%	87%	64%	90%	41%	45%	90%	83%	29%	25%

Transmission Investment ~ Cost of wiring generators together within a "farm"

Capacity Factor = Actual plant output / Maximum possible output:

Low for "simple" gas turbines (OCGT) because they're used for only peak evening power

Low for solar and wind because these are strong for only a fraction of the day

Lowish for hydro because reservoirs are increasingly vulnerable to droughts?

And the BIG one: Capital cost

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Capacity Factor			85%	30%	87%	87%	64%	90%	41%	45%	90%	83%	29%	25%

Capital Cost = THE MAJOR COST for almost every single technology

Exception = Combined Cycle natural gas turbines [1]

Combined Cycle => More power out per fuel => Decreased cost per power output

Solar thermal's capital cost appears very high (but more about this later)

1) For a more complete explanation, see my **Fossil Fuels** (pptx / pdf / key) note set

OK, but aren't costs of renewables falling?

Let me first just give you all of the data (2011-2018)

then I'll come back and look for trends

2011 EIA report on Levelized Cost of New Generation Resources

Which predicts costs of power plants coming on line in 2016:

2011 - US EIA - Levelized Cost of New Generation Resources in the Annual Energy Outlook

	Conventional Coal	Advanced Coal (IGCC)	Sequestered Coal (IGCC)	Natural Gas - Simple Turbine	Natural Gas (CC)	Sequestered Natural Gas (CC+S)	Hydroelectric	Nuclear	Wind - Onshore	Wind - Offshore	Geothermal	Biomass	Solar Photovoltaic	Solar Thermal
Costs in $ / MW-hr:														
Total Cost	94.8	109.4	136.2	124.5	66.1	89.3	86.4	113.9	97.0	243.2	101.7	112.5	210.7	311.8
Fuel + Variable Costs	24.3	25.7	33.1	71.5	45.6	49.6	6.3	11.7	0.0	0.0	9.5	42.3	0.0	0.0
Fixed Operating Costs	3.9	7.9	9.2	3.7	1.9	3.9	3.8	11.1	9.6	28.1	11.9	13.7	12.1	46.6
Capital Cost	65.3	74.6	92.7	45.8	17.5	34.6	74.5	90.1	83.9	209.3	79.3	55.3	194.6	259.4
Transmission Investment	1.2	1.2	1.2	3.5	1.2	1.2	1.9	1.0	3.5	5.9	1.0	1.3	4.0	5.8
Capacity Factor	85%	85%	85%	30%	87%	87%	52%	90%	34%	34%	92%	83%	25%	18%

2012 EIA report on Levelized Cost of New Generation Resources

Which predicts costs of power plants coming on line in 2017:

2012 - US EIA - Levelized Cost of New Generation Resources in the Annual Energy Outlook

	Conventional Coal	Advanced Coal (IGCC)	Sequestered Coal (IGCC)	Natural Gas - Simple Turbine	Natural Gas (CC)	Sequestered Natural Gas (CC+S)	Hydroelectric	Nuclear	Wind	Wind - Offshore	Geothermal	Biomass	Solar Photovoltaic	Solar Thermal
Costs in $ / MW-hr:														
Total Cost	97.7	110.9	138.8	127.9	66.1	90.1	88.9	111.4	96.0	N/A	98.2	115.4	152.7	242.0
Fuel + Variable Costs	27.5	29.1	36.4	76.4	45.8	50.6	6.0	11.6	0.0	N/A	9.6	44.3	0.0	0.0
Fixed Operating Costs	4.0	6.6	9.3	2.7	1.9	4.0	4.0	11.3	9.8	N/A	11.9	13.8	7.7	40.1
Capital Cost	64.9	74.1	91.8	45.3	17.2	34.3	76.9	87.5	82.5	N/A	75.1	56.0	140.7	195.6
Transmission Investment	1.2	1.2	1.2	3.6	1.2	1.2	2.1	1.1	3.8	N/A	1.5	1.3	4.3	6.3
Capacity Factor	85%	85%	85%	30%	87%	87%	53%	90%	33%	N/A	91%	83%	25%	20%

2013 EIA report on Levelized Cost of New Generation Resources

Which predicts costs of power plants coming on line in 2018:

2013 - US EIA - Levelized Cost of New Generation Resources in the Annual Energy Outlook

	Conventional Coal	Advanced Coal (IGCC)	Sequestered Coal (IGCC)	Natural Gas - Simple Turbine	Natural Gas (CC)	Sequestered Natural Gas (CC+S)	Hydroelectric	Nuclear	Wind - Onshore	Wind - Offshore	Geothermal	Biomass	Solar Photovoltaic	Solar Thermal
Costs in $ / MW-hr:														
Total Cost	100.1	123.0	135.5	130.3	67.1	93.4	90.3	108.4	86.6	221.9	89.6	111.0	144.3	261.5
Fuel + Variable Costs	29.2	30.7	37.2	80.0	48.4	54.1	6.1	12.3	0.0	0.0	0.0	42.3	0.0	0.0
Fixed Operating Costs	4.1	6.8	8.8	2.7	1.7	4.1	4.1	11.6	13.1	22.4	12.0	14.3	9.9	41.4
Capital Cost	65.7	84.4	88.4	44.2	15.8	34.0	78.1	83.4	70.3	193.4	76.2	53.2	130.4	214.2
Transmission Investment	1.2	1.2	1.2	3.4	1.2	1.2	2.0	1.1	3.2	5.7	1.4	1.2	4.0	5.9
Capacity Factor	85%	85%	85%	30%	87%	87%	52%	90%	34%	37%	92%	83%	25%	20%

2014 EIA report on Levelized Cost of New Generation Resources

Which predicts costs of power plants coming on line in 2019:

2014 - US EIA - Levelized Cost of New Generation Resources in the Annual Energy Outlook	Conventional Coal	Advanced Coal (IGCC)	Sequestered Coal (IGCC)	Natural Gas - Simple Turbine	Natural Gas (CC)	Sequestered Natural Gas (CC+S)	Hydroelectric	Nuclear	Wind - Onshore	Wind - Offshore	Geothermal	Biomass	Solar Photovoltaic	Solar Thermal
Costs in $ / MW-hr:														
Total Cost	95.6	115.9	147.4	128.4	66.3	91.3	84.5	96.1	80.3	204.1	47.9	102.6	130.0	243.1
Fuel + Variable Costs	30.3	31.7	38.6	82.0	82.0	55.6	6.4	11.8	0.0	0.0	0.0	39.5	0.0	0.0
Fixed Operating Costs	4.2	6.9	9.8	2.8	1.7	4.2	4.1	11.8	13.0	22.8	12.2	14.5	11.4	42.1
Capital Cost	60.0	76.1	97.8	40.2	14.3	30.3	72.0	71.4	64.1	175.4	34.2	47.4	114.5	195.0
Transmission Investment	1.2	1.2	1.2	3.4	1.2	1.2	2.0	1.1	3.2	5.8	1.4	1.2	4.1	6.0
Capacity Factor	85%	85%	85%	20%	87%	87%	53%	90%	35%	37%	92%	83%	25%	20%

2015 EIA report on Levelized Cost of New Generation Resources

Which predicts costs of power plants coming on line in 2020:

2015 - US EIA - Levelized Cost of New Generation Resources in the Annual Energy Outlook

	Conventional Coal	Advanced Coal (IGCC)	Sequestered Coal (IGCC)	Natural Gas - Simple Turbine	Natural Gas (CC)	Sequestered Natural Gas (CC+S)	Hydroelectric	Nuclear	Wind - Onshore	Wind - Offshore	Geothermal	Biomass	Solar Photovoltaic	Solar Thermal
Costs in $ / MW-hr:														
Total Cost	95.1	115.7	144.4	141.5	75.2	100.2	83.5	95.2	73.6	196.9	47.6	100.5	125.3	239.7
Fuel + Variable Costs	29.4	30.7	36.1	94.6	57.8	64.7	7.0	12.2	0.0	0.0	0.0	37.6	0.0	0.0
Fixed Operating Costs	4.2	6.9	9.8	2.8	1.7	4.2	3.9	11.8	12.8	22.5	12.3	14.5	11.4	42.1
Capital Cost	60.4	76.9	97.3	40.7	14.4	30.1	70.7	70.1	57.7	168.6	34.1	47.1	109.8	191.6
Transmission Investment	1.2	1.2	1.2	3.5	1.2	1.2	2.0	1.1	3.1	5.8	1.4	1.2	4.1	6.0
Capacity Factor	85%	85%	85%	30%	87%	87%	54%	90%	36%	38%	92%	83%	25%	20%

2016 EIA report on Levelized Cost of New Generation Resources

Which predicts costs of power plants coming on line in 2021:

2016 - US EIA - Levelized Cost of New Generation Resources in the Annual Energy Outlook

	Conventional Coal	Advanced Coal (IGCC)	Sequestered Coal (IGCC)	Natural Gas - Simple Turbine	Natural Gas (CC)	Sequestered Natural Gas (CC+S)	Hydroelectric	Nuclear	Wind - Onshore	Wind - Offshore	Geothermal	Biomass	Solar Photovoltaic	Solar Thermal
Costs in $ / MW-hr:														
Total Cost			139.5	110.8	57.2	84.8	67.8	102.8	64.5	158.1	45.0	96.1	84.7	235.9
Fuel + Variable Costs			31.9	59.9	38.9	50.1	4.9	11.3	0.00	0.0	0.0	35.0	0.0	0.0
Fixed Operating Costs			9.2	6.5	1.3	4.3	3.6	12.4	13.2	19.3	12.6	14.9	9.9	43.3
Capital Cost			97.2	40.9	15.8	29.2	57.5	78.0	48.5	134.0	30.9	44.9	70.7	186.6
Transmission Investment			1.2	3.4	1.2	1.2	1.9	1.1	2.8	4.8	1.4	1.2	4.1	6.0
Capacity Factor			85%	30%	87%	87%	58%	90%	40%	45%	91%	83%	25%	20%
Total Cost - Tax Credit									56.9	146.7	41.9		66.3	179.9

2017 EIA report on Levelized Cost of New Generation Resources

Which predicts costs of power plants coming on line in 2022:

2017 - US EIA - Levelized Cost of New Generation Resources in the Annual Energy Outlook	Conventional Coal	Advanced Coal (IGCC)	Sequestered Coal (IGCC)	Natural Gas - Simple Turbine	Natural Gas (CC)	Sequestered Natural Gas (CC+S)	Hydroelectric	Nuclear	Wind - Onshore	Wind - Offshore	Geothermal	Biomass	Solar Photovoltaic	Solar Thermal
Costs in $ / MW-hr:														
Total Cost			140.0	109.4	56.5	82.4	66.2	99.1	63.7	157.4	46.5	102.4	85.0	242.0
Fuel + Variable Costs			34.6	58.6	38.1	47.4	4.8	11.7	0.0	0.0	0.0	41.2	0.00	0.0
Fixed Operating Costs			9.3	6.6	1.3	4.4	3.4	12.6	13.7	19.6	12.8	15.2	10.50	44.0
Capital Cost			94.9	40.7	15.8	29.5	56.2	73.6	47.2	133.0	32.2	44.7	70.2	191.9
Transmission Investment			1.2	3.5	1.2	1.2	1.8	1.1	2.8	4.8	1.5	1.3	4.40	6.10
Capacity Factor			85%	30%	87%	87%	59%	90%	39%	45%	91%	83%	24%	20%
Total Cost - Tax Credit									52.2	145.9	43.3		66.8	184.4

2018 EIA report on Levelized Cost of New Generation Resources

Which predicts costs of power plants coming on line in 2023:

2018 - US EIA - Levelized Cost of New Generation Resources in the Annual Energy Outlook

	Conventional Coal	Advanced Coal (IGCC)	Sequestered Coal (IGCC)	Natural Gas - Simple Turbine (CT)	Natural Gas (CC)	Sequestered Natural Gas (CC+S)	Hydroelectric	Nuclear	Wind - Onshore	Wind - Offshore	Geothermal	Biomass	Solar Photovoltaic	Solar Thermal
Costs in $ / MW-hr:														
Total Cost			119.1	85.1	50.1	74.9	61.7	92.6	59.1	138.0	44.6	95.3	63.2	165.1
Fuel + Variable Costs			38.5	55.7	34.9	42.5	1.8	9.3	0.0	0.0	0.0	39.6	0.00	0.0
Fixed Operating Costs			11.0	2.6	1.5	4.4	9.8	12.9	13.4	19.9	13.2	15.4	8.70	32.6
Capital Cost			68.5	23.6	12.6	26.9	56.2	69.4	43.1	115.8	30.2	39.2	51.2	128.4
Transmission Investment			1.1	3.5	1.1	1.1	1.9	1.0	2.5	2.3	1.4	1.1	3.30	4.10
Capacity Factor			85%	30%	87%	87%	64%	90%	41%	45%	90%	83%	29%	25%
Total Cost - Tax Credit									48	117	41.6		49.9	126.6

Now COMPARING those seven years of EIA LCOE reports:

Total Levelized Costs vs. Year	Conventional Coal	Advanced Coal (IGCC)	Sequestered Coal (IGCC)	Natural Gas - Simple Turbine	Natural Gas (CC)	Sequestered Natural Gas (CC)	Hydroelectric	Nuclear	Wind - Onshore	Wind - Offshore	Geothermal	Biomass	Solar Photovoltaic	Solar Thermal
2011 Report	94.8	109.4	136.2	124.5	66.1	89.3	86.4	113.9	97.0	243.2	101.7	112.5	210.7	311.8
2012 Report	97.7	110.9	138.8	127.9	66.1	90.1	88.9	111.4	96.0	N/A	98.2	115.4	152.7	242.0
2013 Report	100.1	123.0	135.5	128.4	67.1	93.4	90.3	108.4	86.6	221.9	89.6	111.0	144.3	261.5
2014 Report	95.6	115.9	147.4	141.5	66.3	91.3	84.5	96.1	80.3	204.1	47.9	102.6	130.0	243.1
2015 Report	95.1	115.7	144.4	141.5	75.2	100.2	83.5	95.2	73.6	196.9	47.6	100.5	125.3	239.7
2016 Report			139.5	110.8	57.2	84.8	67.8	102.8	64.5	158.1	45.0	96.1	84.7	235.9
2017 Report			140.0	109.4	56.5	82.4	66.2	99.1	63.7	157.4	46.5	102.4	85.0	242.0
2018 Report			119.1	85.1	50.1	74.9	61.7	92.6	59.1	138.0	44.6	95.3	63.2	165.1

First some quirky observations (bearing on the accuracy of EIA reports):

The EIA seems to be having trouble assessing **offshore wind power:**

Even dropping it completely from their 2012 report

Likely explanation?

Absence of U.S. offshore wind farms + their rapid technological evolution

EIA also seems to be having trouble with hydroelectric & geothermal:

Total Levelized Costs vs. Year

	Conventional Coal	Advanced Coal (IGCC)	Sequestered Coal (IGCC)	Natural Gas - Simple Turbine	Natural Gas (CC)	Sequestered Natural Gas (CC)	Hydroelectric	Nuclear	Wind - Onshore	Wind - Offshore	Geothermal	Biomass	Solar Photovoltaic	Solar Thermal
2011 Report	94.8	109.4	136.2	124.5	66.1	89.3	86.4	113.9	97.0	243.2	101.7	112.5	210.7	311.8
2012 Report	97.7	110.9	138.8	127.9	66.1	90.1	88.9	111.4	96.0	N/A	98.2	115.4	152.7	242.0
2013 Report	100.1	123.0	135.5	128.4	67.1	93.4	90.3	108.4	86.6	221.9	89.6	111.0	144.3	261.5
2014 Report	95.6	115.9	147.4	141.5	66.3	91.3	84.5	96.1	80.3	204.1	47.9	102.6	130.0	243.1
2015 Report	95.1	115.7	144.4	141.5	75.2	100.2	83.5	95.2	73.6	196.9	47.6	100.5	125.3	239.7
2016 Report			139.5	110.8	57.2	84.3	67.8	102.8	64.5	158.[illegible]	45.0	96.1	84.7	235.9
2017 Report			140.0	109.4	56.5	82.4	66.2	99.1	63.7	157.4	46.5	102.4	85.0	242.0
2018 Report			119.1	85.1	50.1	74.9	61.7	92.6	59.1	138.0	44.6	95.3	63.2	165.1

Cost of very mature hydroelectric power plants plunging in just **two** years?

Cost of geothermal power plunging in just **one** year?

Yes, geothermal **is** a young and still maturing technology

But cost falling by almost **50%** in one year?

Shortcomings in EIA assessment techniques seem more plausible!

And why are coal data missing from the last two reports?

Total Levelized Costs vs. Year	Conventional Coal	Advanced Coal (IGCC)	Sequestered Coal (IGCC)	Natural Gas - Simple Turbine	Natural Gas (CC)	Sequestered Natural Gas (CC)	Hydroelectric	Nuclear	Wind - Onshore	Wind - Offshore	Geothermal	Biomass	Solar Photovoltaic	Solar Thermal
2011 Report	94.8	109.4	136.2	124.5	66.1	89.3	86.4	113.9	97.0	243.2	101.7	112.5	210.7	311.8
2012 Report	97.7	110.9	138.8	127.9	66.1	90.1	88.9	111.4	96.0	N/A	98.2	115.4	152.7	242.0
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2017 Report			140.0	109.4	56.5	82.4	66.2	99.1	63.7	157.4	46.5	102.4	85.0	242.0
2018 Report			119.1	85.1	50.1	74.9	61.7	92.6	59.1	138.0	44.6	95.3	63.2	165.1

Easy (but depressing) explanation: EIA projects cost for NEW power plants

In 2016 the U.S. banned new coal plants lacking CO_2 sequestration

Leading EIA to drop them from their report

(Surviving 3rd column is for coal plants with partial CO_2 sequestration)

With "WAR ON COAL" ended, can we now expect their resurrection?

Finally comparing levelized **capital costs** *for* **all technologies**

Levelized Capital Costs vs. Year	Conventional Coal	Advanced Coal (IGCC)	Sequestered Coal (IGCC)	Natural Gas - Simple Turbine	Natural Gas (CC)	Sequestered Natural Gas (CC)	Hydroelectric	Nuclear	Wind - Onshore	Wind - Offshore	Geothermal	Biomass	Solar Photovoltaic	Solar Thermal
2011 Report	65.3	74.6	92.7	45.8	17.5	34.6	74.5	90.1	83.9	209.3	79.3	55.3	194.6	259.4
2012 Report	64.9	74.1	91.8	45.3	17.2	34.3	76.9	87.5	82.5	N/A	75.1	56.0	140.7	195.6
2013 Report	65.7	84.4	88.4	44.2	15.8	34.0	78.1	83.4	70.3	193.4	76.2	53.2	130.4	214.2
2014 Report	60.0	76.1	97.8	40.2	14.3	30.3	72.0	71.4	64.1	175.4	34.2	47.4	114.5	195.0
2015 Report	60.4	76.9	97.3	40.7	14.4	30.1	70.7	70.1	57.7	168.6	34.1	47.1	109.8	191.6
2016 Report			97.2	40.9	15.8	29.2	57.5	78.0	48.5	134.0	30.9	44.9	70.7	186.6
2017 Report			94.9	40.7	15.8	29.5	56.2	73.6	47.2	133.0	32.2	44.7	70.2	191.9
2018 Report			68.5	23.6	12.6	26.9	56.2	69.4	43.1	115.8	30.2	39.2	51.2	128.4

Capital costs for cleaner but still carbon-emitting **natural gas** plants have fallen

As have costs for non-carbon-emitting **hydro**, **nuclear**, **wind**, **geothermal** & **solar**

Decreases have been particularly strong, or sustained, or plausible for:

Onshore wind **and** **Solar PV**

OR comparing levelized **total costs** *for* **all technologies**

Total Levelized Costs vs. Year	Conventional Coal	Advanced Coal (IGCC)	Sequestered Coal (IGCC)	Natural Gas - Simple Turbine	Natural Gas (CC)	Sequestered Natural Gas (CC)	Hydroelectric	Nuclear	Wind - Onshore	Wind - Offshore	Geothermal	Biomass	Solar Photovoltaic	Solar Thermal
2011 Report	94.8	109.4	136.2	124.5	66.1	89.3	86.4	113.9	97.0	243.2	101.7	112.5	210.7	311.8
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2016 Report			139.5	110.8	57.2	84.8	67.8	102.8	64.5	158.1	45.0	96.1	84.7	235.9
2017 Report			140.0	109.4	56.5	82.4	66.2	99.1	63.7	157.4	46.5	102.4	85.0	242.0
2018 Report			119.1	85.1	50.1	74.9	61.7	92.6	59.1	138.0	44.6	95.3	63.2	165.1

Total cost trends closely resemble those of capital costs alone

Reflecting the prominence of capital cost in determining final energy prices

The big bottom line conclusion (based on green labeled < 90 numbers)?

All but two lowest cost technologies (natural gas) are now renewables!

With total costs well below that of even resurrected "conventional (dirty) coal"

Something (else) that bothered me about EIA reports:

EIA never mentions what TYPE of solar PV plant they are evaluating

I assumed it would be single crystal silicon solar cells

Which concerned me because high energy UV sunlight can degrade PV's

Single crystal Si is the toughest stuff with lifetime of at least 20 years

Polycrystalline Si is a bit less tough and might last ~ 15 years

Really cheap organic material cells may only last few months / years

But levelized costing assumes financing of projects over their whole lifespan

So EIA analysis SHOULD have taken power plant lifetimes into account

I dug and dug, and the ONLY place EIA mentioned lifetime was in a tax section

Where they used a **30 year lifetime for ALL types of power plants**

I couldn't believe EIA ignored technology lifetimes!

So I wrote Prof. Edward S. Rubin (of Carnegie Melon)

Author of respected "Introduction to Engineering and the Environment"

He confirmed that EIA reports assume 30 year lifetimes **for everything**

DESPITE the likely shorter (and technology specific) lifetimes of solar PV

DESPITE the fact that nuclear plants are regularly licensed for 40 years of operation

And many are now being re-licensed for 1-2 decades of more use

DESPITE the fact that commonly assumed lifetime of hydroelectric dams is 100 years

And Hoover Dam is actually showing few signs of ANY aging at 75

So I decided to try and correct the EIA data by taking likely lifetimes into account

Combining EIA data with earlier tutorial on levelized costs:

For almost all power generation technologies:

Levelized CAPITAL cost = 2/3 – 7/8 of TOTAL levelized annual power cost

(With notable exception of natural gas using cheap jet engine turbines)

But **levelized annual** capital cost = (up front capital cost) x U/P (i interest, n years)

Where, $U/P\ (n, i) = i\ /\ [1 - (1+i)^{-n}]$

And although EIA used n = 30 years for ALL different types of power plants

As a technologist, I am telling you they should have used values more like:

n ~ 100 years for hydro
n ~ 40-60 years for nuclear
n ~ 30 years for coal and possibly gas, wind, geothermal and solar thermal
n ~ 20 years for silicon single crystal solar PV
n ~ 10 (or less) "emerging" PV technologies such as organic PV

So to correct EIA data for likely power plant lifetimes:

EIA's levelized capital costs need to be adjusted by factor of:

U/P (actual plant lifetime, i) / U/P (30 year lifetime, i)

And given the heavy contribution of capital cost to total cost

Correction **almost as large** should be applied to total cost of most plants

I need to know EIA's assumed interest rate, which I didn't spot in EIA reports

But elsewhere I found data on **overnight capital cost** of some plants

= capital + labor + materials cost to build a power plant

This present value (P) x U/P (i=?, 30 yrs) should => EIA's levelized capital cost

Found I could fit EIA conversion to levelized capital cost with i = 10-15%

10-15% interest sounds very high, but this is a relatively risky investment:

If goes bust (and they do!) no one may be willing to buy that power plant!

Calculating my proposed correction to EIA data:

Correction factor (using my fitting value of i ~ 12.5%):

U/P (actual plant lifetime, 12.5%) / U/P (EIA's 30 year lifetime, 12.5%)

$= \{i / [1 - (1+i)^{-\text{actual lifetime}}]\} / \{[i / [1 - (1+i)^{-30}]\}$

$= [1 - (1.125)^{-30}] / [1 - (1.125)^{-\text{actual lifetime}}]$

For which I get these values:

Actual lifetime (years):	10	20	30	40	60	100
Correction factor:	1.402	1.072	1	0.979	0.9716	0.9709

Emerging PV is 40% higher, Si PV 7% higher, nuclear/hydro 3% lower

Why, if 20 year Si PV lasts half as long as 40 year nuclear, is difference only 10%?

Won't I have to buy TWO PV plants to match ONE nuclear plant?

And thus have to double my charges for PV power to break even?

It would mean that IF your investors expected zero interest:

Your mortgage/bond payments cover two things:

- Repayment of the loan (P)
- Interest on the remaining loan balance

Tiny interest rate / short loan: Almost all of payment => paying down loan

And the remaining balance on that loan drops ~ linearly with time

Finite interest rate / long loan: Almost all of payment => interest on loan

And, initially, the remaining balance on the loan drops hardly at all!

The latter is the origin of the homeowners lament that:

"I don't really own my home, I just rent it from my bank!"

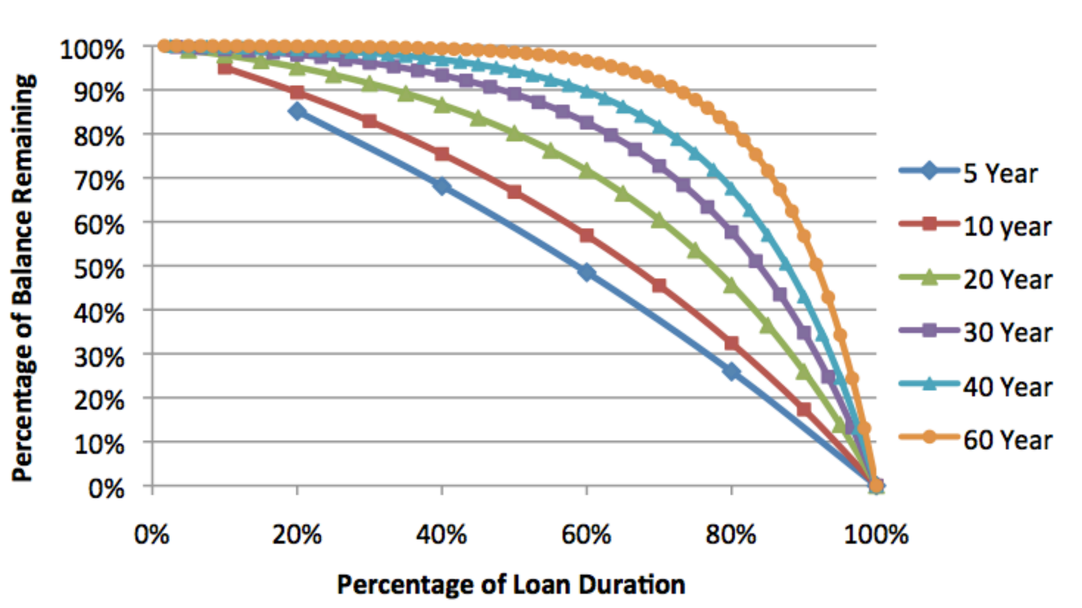
As revealed by plot of balance remaining on various loans:

Balance remaining on a loan is:

Balance (i, n = number of loan intervals, m = this loan interval)

$$= \text{Loan}\ \{1 - [(1+i)^n - (1+i)^m]/[(1+i)^n - 1]\}$$

My Excel plot of Balance on Loan vs. m/n (= percentage of the loan's lifetime)



For loans of labeled duration

With interest Rates of i = 15%

Homeowners are right: With long loans initial payments are ~ all interest!

Calculating the advantage of getting power plants to last longer:

Three different power plant technologies **with same capital cost & power output**

But **Tech10** lasts 10 years, **Tech20** last 20 years, **Tech40** lasts 40 years

For 40 years of power I'll need 4 Tech10 plants, 2 Tech20 plants or 1 Tech40 plant

Assume I'll finance each of these with loans lasting plant lifetime, at 12.5% interest

Total cost = (# of loans) x (# payments per loan) x (payment amount)

Giving, for the three different alternatives supplying 40 years of power:

Tech10 Total cost = (4 loans) (10 payments) [P x **U/P(12.5%, 10 yrs)**]

Tech20 Total cost = (2 loans) (20 payments) [P x **U/P(12.5%, 20 yrs)**]

Tech40 Total cost = (1 loan) (40 payments) [P x **U/P(12.5%, 40 yrs)**]

Pulling up U/P uniform payment table

With data highlighted for our 10, 20 or 40 year long 12.5% interest loans

U/P (i, n) tables = i / [1- (1+i)^-n]

i =	3%	i =	4%	i =	5%	i =	10%	i =	12.5%	i =	15%
n	U/P	n	U/P	n	U/P	n	U/P	n	U/P	n	U/P
1	1.0300	1	1.0400	1	1.0500	1	1.1000	1	1.1250	1	1.1500
2	0.5226	2	0.5302	2	0.5378	2	0.5762	2	0.5956	2	0.6151
3	0.3535	3	0.3603	3	0.3672	3	0.4021	3	0.4199	3	0.4380
4	0.2690	4	0.2755	4	0.2820	4	0.3155	4	0.3327	4	0.3503
5	0.2184	5	0.2246	5	0.2310	5	0.2638	5	0.2809	5	0.2983
6	0.1846	6	0.1908	6	0.1970	6	0.2296	6	0.2467	6	0.2642
7	0.1605	7	0.1666	7	0.1728	7	0.2054	7	0.2226	7	0.2404
8	0.1425	8	0.1485	8	0.1547	8	0.1874	8	0.2048	8	0.2229
9	0.1284	9	0.1345	9	0.1407	9	0.1736	9	0.1913	9	0.2096
10	0.1172	10	0.1233	10	0.1295	10	0.1627	10	0.1806	10	0.1993
15	0.0838	15	0.0899	15	0.0963	15	0.1315	15	0.1508	15	0.1710
20	0.0672	20	0.0736	20	0.0802	20	0.1175	20	0.1381	20	0.1598
30	0.0510	30	0.0578	30	0.0651	30	0.1061	30	0.1288	30	0.1523
40	0.0433	40	0.0505	40	0.0583	40	0.1023	40	0.1261	40	0.1506
50	0.0389	50	0.0466	50	0.0548	50	0.1009	50	0.1253	50	0.1501
60	0.0361	60	0.0442	60	0.0528	60	0.1003	60	0.1251	60	0.1500
70	0.0343	70	0.0427	70	0.0517	70	0.1001	70	0.1250	70	0.1500
80	0.0331	80	0.0418	80	0.0510	80	0.1000	80	0.1250	80	0.1500
90	0.0323	90	0.0412	90	0.0506	90	0.1000	90	0.1250	90	0.1500
100	0.0316	100	0.0408	100	0.0504	100	0.1000	100	0.1250	100	0.1500

Source: My Excel spreadsheets – as included at the end of this lecture note set

Inserting those ratios of payments/loan amount (U/P):

Tech10 total cost = P x 4 x 10 x **U/P(12.5%, 10 yrs) =** 40 P x (0.1806) = 7.224 P

Tech20 total cost = P x 2 x 20 x **U/P(12.5%, 20 yrs) =** 40 P x (0.1381) = 5.524 P

Tech40 total cost = P x 1 x 40 x **U/P(12.5%, 40 yrs) =** 40 P x (0.1261) = 5.044 P

Assuming "overnight construction cost" is identical for all of these plants (=> P):

Non-surprise: Cost of 4 short-lived Tech10 plants is a lot more!

7.224 / 5.044 = 1.43: Four Tech10's **cost 43% more** than one Tech40

Surprise: Cost of 2 Tech20 plants ~ Cost of 1 Tech40 plant

5.524 / 5.044 = 1.09: Four Tech10's **cost 9% more** than one Tech40

THIS is why EIA economists didn't worry about plant lifetimes!

Once lifetimes get up to 20 years, capital costs get buried under "cost of money"

With ALMOST ALL of each payment covering **that** expense!

*But plant lifetimes are not **quite** irrelevant:*

Lifetime WILL STILL BE AN ISSUE for shorter-lived technologies

For instance, for emerging non-silicon thin-film & organic photovoltaics

with possible lifetimes of 10 years or less,

=> 50% or greater increase in resulting levelized cost of power

Long lifetime plant decisions are also affected by "cost of money"

Say your plant will run efficiently for 30 years

But could run (with more fuel and maintenance) for another 10 years

Would it make more sense to finance and operate it for 30 or 40 years?

The answer could well be "30 years"

Because at 30 years ~ same loan payment could buy a new plant

Which would then require less fuel and maintenance

So EIA really didn't mess up!

I overestimated effect of plant lifetimes because:

I didn't account for "Engineering Economics" / "cost of money"

But the preceding analysis raises another question:

Why not just finance a 40 year nuclear plant with a 20 year mortgage?

Your cumulative loan payment costs would be almost halved

For the same cumulative 40 years of power production!

But for first 20 years you'd have loan payments => higher costs / lower profits

This would likely **clobber** your early stock price & dividend payments

which, taking the "time value of money" into account,

would erode the lifetime investment value of your power plant

Back to LCOE data:

Many energy industry insiders question the EIA's accuracy

Just as I, above, raised doubts about the EIA's analysis of:

Offshore vs. Onshore Wind, Hydroelectricity and Geothermal

Energy industry insiders prefer data from a commercial energy consulting firm:

Lazard's Levelized Cost of Energy Analysis [1]

Lazard has posted a public summary of their 2017 Version 11.0 Report

It's a 22 page edited version of their full report (for which they charge clients)

It presents decidedly more complex and nuanced data than that of the EIA

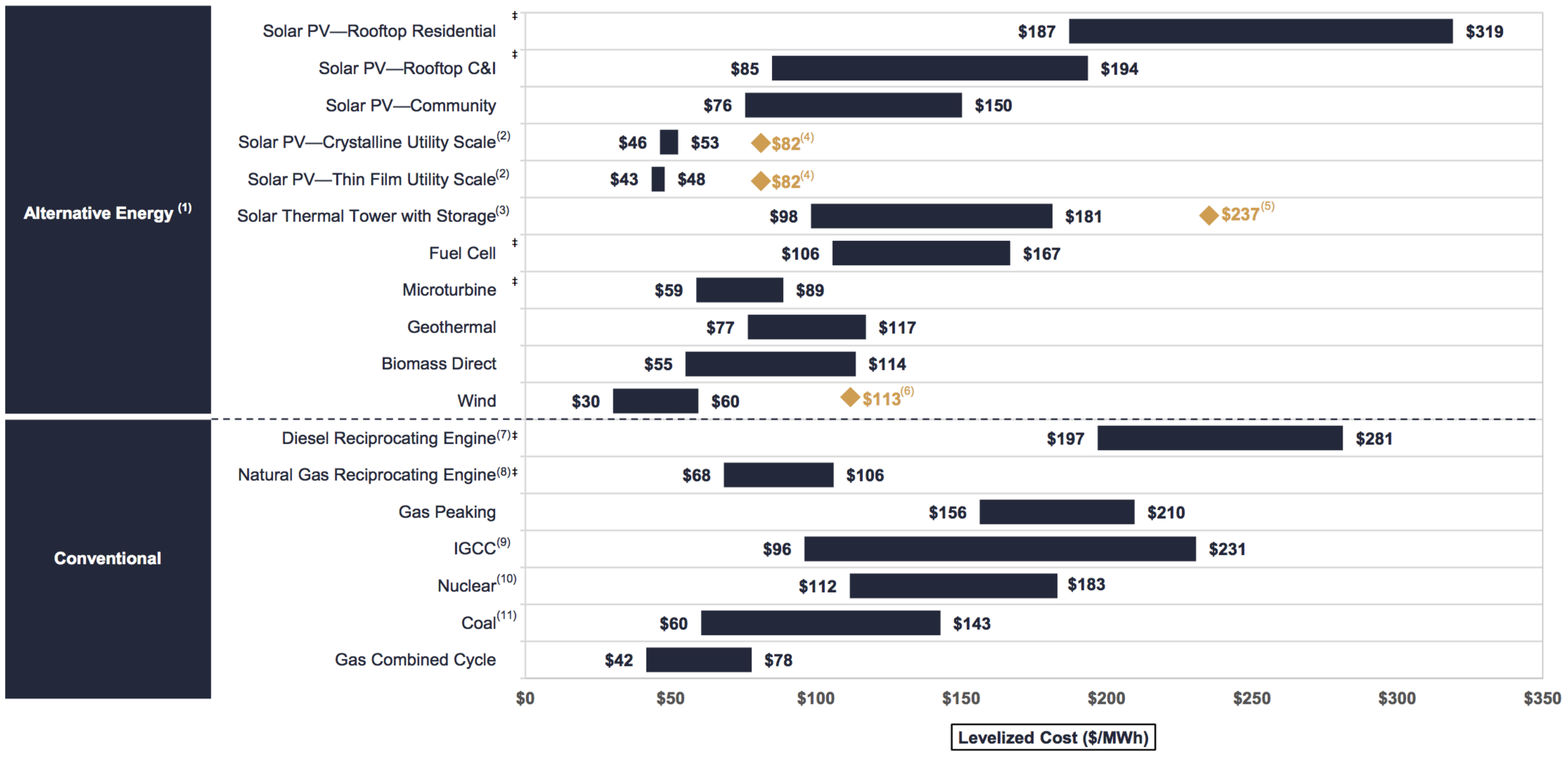
But that presentation can be cryptic (at least to we energy **outsiders**)

For details you've just got to **pay** for the full report!

(But I personally thank Lazard for the public service provided by their summaries!)

1) Lazard Summaries of their V8 (2014), V10 (2016), V11(2017) reports are on the Resources Webpage

Lazard 2016: Unsubsidized levelized costs of energy:



The bands represent typical data spreads for each technology

But diamonds are for often very important special cases

With each of those special cases then explained in a must-read set of:

Footnotes:

(1) Analysis excludes integration (e.g., grid and conventional generation investment to overcome system intermittency) costs for intermittent technologies.

(2) Low end represents single-axis tracking system. High end represents fixed-tilt design. Assumes 30 MW system in a high insolation jurisdiction (e.g., Southwest U.S.). Does not account for differences in heat coefficients within technologies, balance-of-system costs or other potential factors which may differ across select solar technologies or more specific geographies.

(3) Low and high end represent a concentrating solar tower with 10-hour storage capability. Low end represents an illustrative concentrating solar tower built in South Australia.

(4) Illustrative “PV Plus Storage” unit. PV and battery system (and related bi-directional inverter, power control electronics, etc.) sized to compare with solar thermal with 10-hour storage on capacity factor basis (52%). Assumes storage nameplate “usable energy” capacity of ~400 MWhdc, storage power rating of 110 MWac and ~200 MWac PV system. Implied output degradation of ~0.40%/year (assumes PV degradation of 0.5%/year and battery energy degradation of 1.5%/year, which includes calendar and cycling degradation). Battery round trip DC efficiency of 90% (including auxiliary losses). Storage opex of ~$8/kWh-year and PV O&M expense of ~$9.2/kW DC-year, with 20% discount applied to total opex as a result of synergies (e.g., fewer truck rolls, single team, etc.). Total capital costs of ~$3,456/kW include PV plus battery energy storage system and selected other development costs. Assumes 20-year useful life, although in practice the unit may perform longer. Illustrative system located in Southwest U.S.

(5) Diamond represents an illustrative solar thermal facility without storage capability.

(6) Represents estimated implied midpoint of levelized cost of energy for offshore wind, assuming a capital cost range of $2.36 – $4.50 per watt.

(7) Represents distributed diesel generator with reciprocating engine. Low end represents 95% capacity factor (i.e., baseload generation in poor grid quality geographies or remote locations). High end represents 10% capacity factor (i.e., to overcome periodic blackouts). Assumes replacement capital cost of 65% of initial total capital cost every 25,000 operating hours.

(8) Represents distributed natural gas generator with reciprocating engine. Low end represents 95% capacity factor (i.e., baseload generation in poor grid quality geographies or remote locations). High end represents 30% capacity factor (i.e., to overcome periodic blackouts). Assumes replacement capital cost of 65% of initial total capital cost every 60,000 operating hours.

(9) Does not include cost of transportation and storage. Low and high end depicts an illustrative recent IGCC facility located in the U.S.

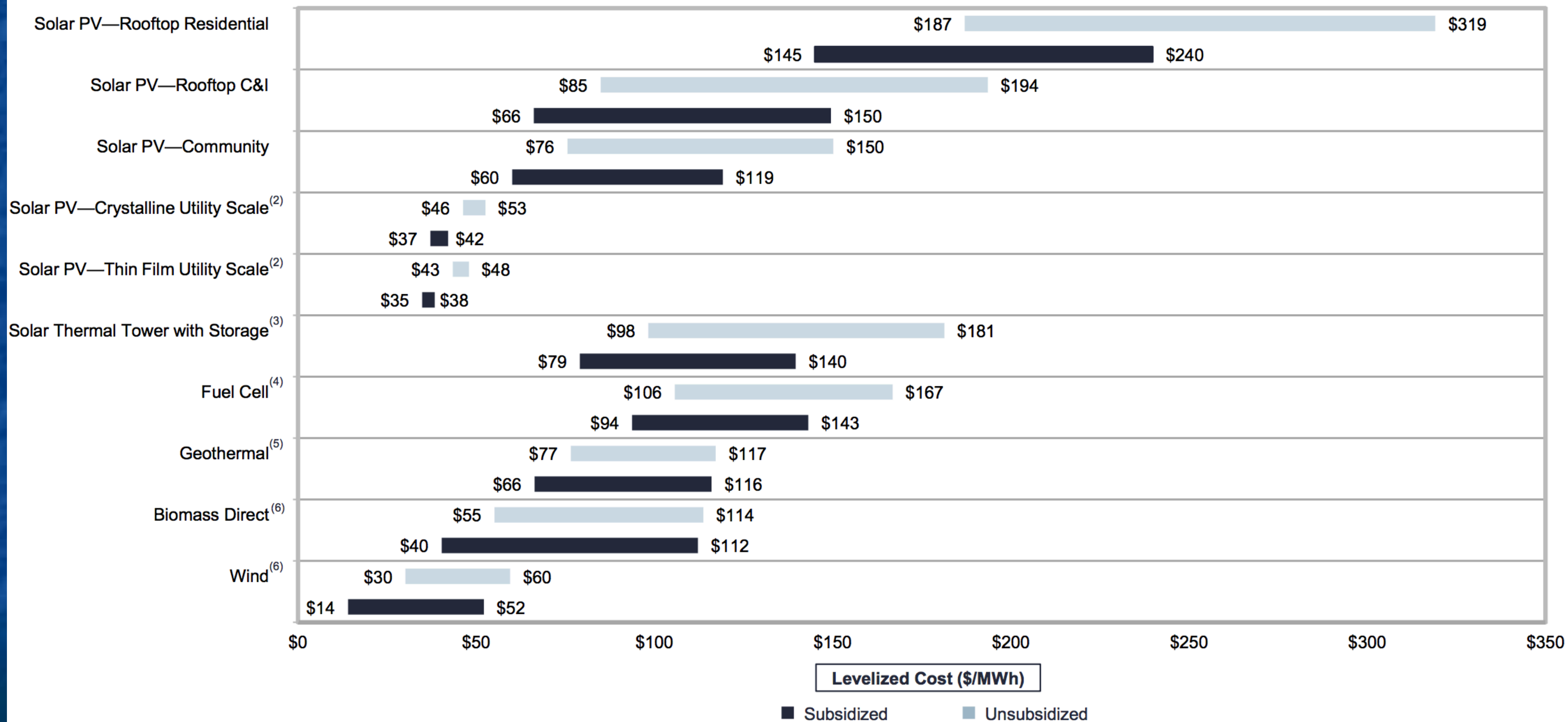
(10) Does not reflect decommissioning costs or potential economic impact of federal loan guarantees or other subsidies. Low and high end depicts an illustrative nuclear plant using the AP1000 design.

(11) Reflects average of Northern Appalachian Upper Ohio River Barge and Pittsburgh Seam Rail coal. High end incorporates 90% carbon capture and compression. Does not include cost of transportation and storage.

The effect of the U.S. Investment Tax Credit is then shown by:

Levelized Cost of Energy—Sensitivity to U.S. Federal Tax Subsidies[1]

Given the extension of the Investment Tax Credit ("ITC") and Production Tax Credit ("PTC") in December 2015 and resulting subsidy visibility, U.S. federal tax subsidies remain an important component of the economics of Alternative Energy generation technologies (and government incentives are, generally, currently important in all regions)



Note the key at the bottom: ■ = Unsubsidized ■ = Subsidized

Things that jump out at me: The effect of scale upon Solar PV:

Solar Photovoltaic costs PLUMMET with the size of their installation:

Residential Rooftop PV:	187-319	$/MW-h
Community PV:	76-150	$/MW-h
Utility Scale Crystal PV:	46-53	$/MW-h
Utility Scale Thin Film PV:	43-48	$/MW-h

Personal solar is at least **2X AS EXPENSIVE** as community scale solar!

And **4X to 6X AS EXPENSIVE** as utility scale solar farms!

Things that jump out at me: Solar w/o Storage versus with it

Lazard's **Solar Thermal w/o Energy Storage** (diamond) = **237 $/MW-h**

Their **Solar Thermal WITH built-in Storage = 98–181 $/MW-h**

Cost of energy storage = 56 - 139 $/MW-h ~ cost of energy generation!

In 2017, the EIA gave their (only) solar thermal number as 242 $/MW-h

But in 2018, EIA's solar thermal number plummeted to 165 $/MW-h

Suggesting EIA's has started assuming solar thermal WITH storage

(though I could no confirmation of that in their 2018 report)

Isn't solar thermal WITH storage still much more expensive than solar PV?

Solar w/o Storage versus with it (cont'd)

Solar Thermal WITH built-in Storage = 98–181 $/MW-h

vs.

Utility Scale Solar PV = 43-53 $/MW-h

That's an apple to orange comparison because to become a major Grid power supplier

Solar PV plants will have to add ways of storing their power until evening/night

Which, Lazard predicts => **Solar PV with Storage** (diamonds) **= 82 $/MW-h**

That's getting close to **Solar Thermal with Storage = 98–181 $/MW-h**

And as a still very young technology, Solar Thermal may yet close that gap!

Things that jump out at me: Cost of wind

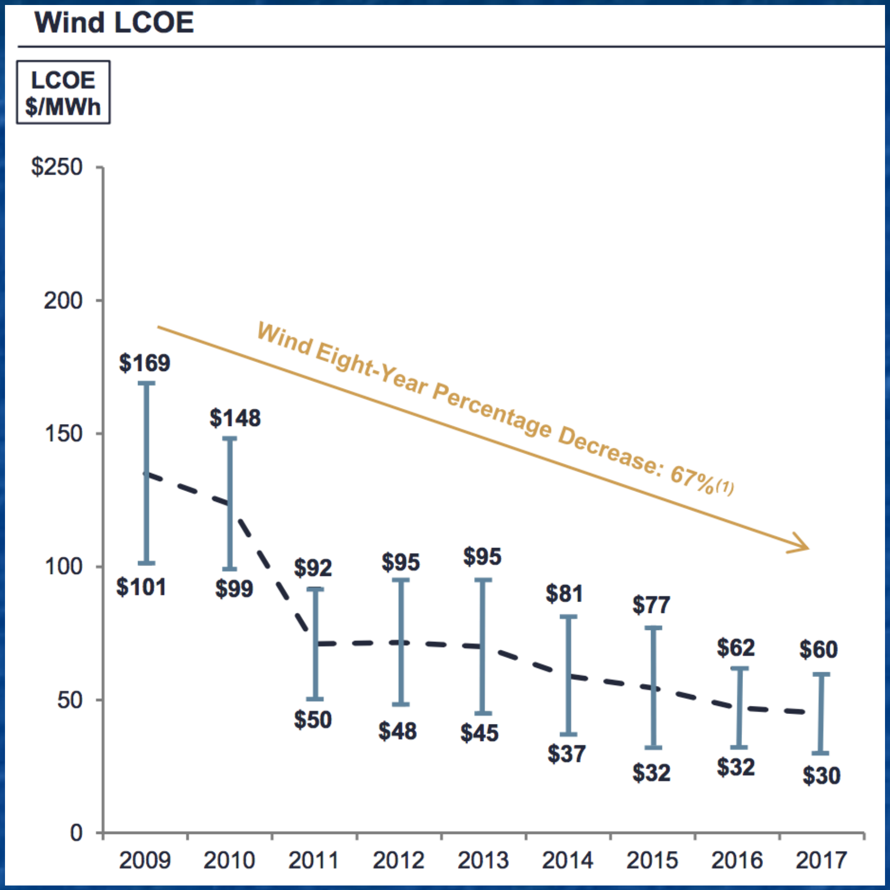
Lazard's **absolutely lowest cost** is for **Onshore Wind = 30-60 $/MW-h**

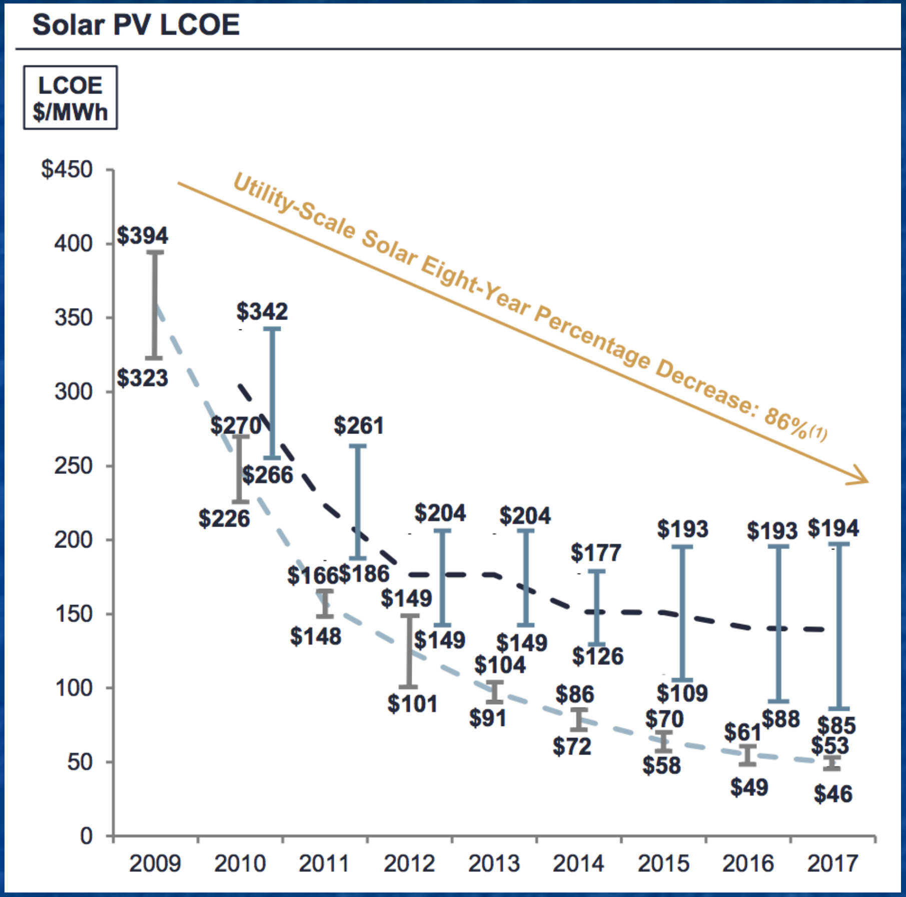
And not too far from being competitive is **Offshore Wind = 113 $/MW-h**

But the biggest thing that jumps out at me is top vs. bottom of the table:

Renewable vs. Non-renewable ranges are now fully comparable!
With wind beating all, and utility solar PV challenged by only CCGT gas

Compound this with Lazard's optimistic take on Renewable trends:





But might this still undervalue renewables?

After all, Lazard's business is that of supplying information to the energy industry

Such large & old industries are rarely known for their embrace of innovation

(Here I speak as a 20+ year former employee of the Bell System)

Could their conservatism have rubbed off on Lazard?

Bloomberg & **The World Energy Council** are **advocates** for sustainable energy

In 2013 they released their own study of renewable LCOE's [1]

Their LCOE's were in **excellent agreement** with Lazard's 2014 report

Both citing renewable LCOE's generally **lower** than EIA estimates

Bloomberg did release an updated LCOE report in 2017

But, unfortunately, I cannot now update my comparisons because:

Unlike Lazard, Bloomberg no longer publically discloses their data!

1) Publically available 2013 and 2017 Bloomberg documents are also available on my Resources Webpage

LCOE's: EIA 2018 vs. Lazard 2017

	EIA	Lazard
Sequestered IGCC Coal	119.1	143 [1]
Natural Gas CC (CCGT)	50.1	42-78
Natural Gas Peaking (OCGT)	85.1	156-210
Hydroelectric	61.7	
Nuclear	92.6	112-183
Biomass - no subsidy (subsidized)	95.3	55-114 (40-112)
Geothermal - no subsidy (subsidized)	44.6 (41.6)	77-117 (64-116)
Wind Onshore- no subsidy (subsidized)	59.1 (48)	30-60 (14-52)
Wind Offshore - no subsidy (subsidized)	138.0 (117.1)	113
Solar PV	63.2 (49.9)	
Si crystalline PV – utility - no subsidy (subsidized)		46-53 (37-42)
Thin Film PV – utility - no subsidy (subsidized)		43-48 (35-48)
Solar Thermal w/o Storage - no subsidy (subsidized)		237
Solar Thermal w/ Storage - no subsidy (subsidized)	165.1? (126.6)?	98-181 (79-140)

1) Lazard gives sequestered IGCC coal as being at the top of their bar = 143 (footnote 11)

Highlights of that EIA 2018 to Lazard 2017 comparison:

Notable Points of Disagreement:

Lazard LCOE for natural gas peaking (OCGT) is substantially higher

Lazard LCOE for geothermal is substantially higher

Lazard LCOE for onshore wind has a range extending much lower

Lazard LCOE for offshore wind is substantially lower

Lazard LCOEs for utility scale solar PV are substantially lower

Suggesting that EIA's solar PV number is biased toward residential PV

Notable Point of Complete Agreement:

The cost of sequestered coal is completely non-competitive

Highlighting areas of agreement & disagreement:

Strong Agreement vs. *Strong Disagreement*

	EIA	Lazard
Sequestered IGCC Coal	119.1	143 [1]
Natural Gas CC (CCGT)	50.1	42-78
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Solar Thermal w/ Storage - no subsidy (subsidized)	165.1? (126.6)?	98-181 (79-140)

If Lazard's right, why aren't we seeing massive U.S. wind & solar investment?

Well it turns out that we ARE now investing massively in **onshore wind**

More than in any other current technology!

And, with the possibility of sighting **offshore wind** out-of-sight:

We are **finally** beginning to build offshore wind farms

But it looks like the EIA **and we citizens** have been too focused upon our rooftops

Rooftop solar PV is just not competitive with most energy alternatives

This will worsen as renewables grow to the point that we need **storage**

Instead, **community and utility scale solar PV** now make a lot more sense

Finally, with its natural ability to integrate energy storage

We should keep a close watch upon developments in **solar thermal power**

Credits / Acknowledgements

Some materials used in this class were developed under a National Science Foundation "Research Initiation Grant in Engineering Education" (RIGEE).

Other materials, including the WeCanFigureThisOut.org "Virtual Lab" science education website, were developed under even earlier NSF "Course, Curriculum and Laboratory Improvement" (CCLI) and "Nanoscience Undergraduate Education" (NUE) awards.

This set of notes was authored by John C. Bean who also created all figures not explicitly credited above.

Note: Tables of U/P, P/U, F/P and P/F follow this slide

My tables of U/P (i, n):

From my Excel spreadsheet (checked against Rubin's textbook tables):

U/P (i, n) tables = i / [1- (1+i)^-n]

i =	3%		i =	4%		i =	5%		i =	10%		i =	12.5%		i =	15%
n	U/P		n	U/P		n	U/P		n	U/P		n	U/P		n	U/P
1	1.0300		1	1.0400		1	1.0500		1	1.1000		1	1.1250		1	1.1500
2	0.5226		2	0.5302		2	0.5378		2	0.5762		2	0.5956		2	0.6151
3	0.3535		3	0.3603		3	0.3672		3	0.4021		3	0.4199		3	0.4380
4	0.2690		4	0.2755		4	0.2820		4	0.3155		4	0.3327		4	0.3503
5	0.2184		5	0.2246		5	0.2310		5	0.2638		5	0.2809		5	0.2983
6	0.1846		6	0.1908		6	0.1970		6	0.2296		6	0.2467		6	0.2642
7	0.1605		7	0.1666		7	0.1728		7	0.2054		7	0.2226		7	0.2404
8	0.1425		8	0.1485		8	0.1547		8	0.1874		8	0.2048		8	0.2229
9	0.1284		9	0.1345		9	0.1407		9	0.1736		9	0.1913		9	0.2096
10	0.1172		10	0.1233		10	0.1295		10	0.1627		10	0.1806		10	0.1993
15	0.0838		15	0.0899		15	0.0963		15	0.1315		15	0.1508		15	0.1710
20	0.0672		20	0.0736		20	0.0802		20	0.1175		20	0.1381		20	0.1598
30	0.0510		30	0.0578		30	0.0651		30	0.1061		30	0.1288		30	0.1523
40	0.0433		40	0.0505		40	0.0583		40	0.1023		40	0.1261		40	0.1506
50	0.0389		50	0.0466		50	0.0548		50	0.1009		50	0.1253		50	0.1501
60	0.0361		60	0.0442		60	0.0528		60	0.1003		60	0.1251		60	0.1500
70	0.0343		70	0.0427		70	0.0517		70	0.1001		70	0.1250		70	0.1500
80	0.0331		80	0.0418		80	0.0510		80	0.1000		80	0.1250		80	0.1500
90	0.0323		90	0.0412		90	0.0506		90	0.1000		90	0.1250		90	0.1500
100	0.0316		100	0.0408		100	0.0504		100	0.1000		100	0.1250		100	0.1500

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n	P/U	n	P/U	n	P/U	n	P/U	n	P/U	n	P/U
1	0.9709	1	0.9615	1	0.9524	1	0.9091	1	0.8889	1	0.8696
2	1.9135	2	1.8861	2	1.8594	2	1.7355	2	1.6790	2	1.6257
3	2.8286	3	2.7751	3	2.7232	3	2.4869	3	2.3813	3	2.2832
4	3.7171	4	3.6299	4	3.5460	4	3.1699	4	3.0056	4	2.8550
5	4.5797	5	4.4518	5	4.3295	5	3.7908	5	3.5606	5	3.3522
6	5.4172	6	5.2421	6	5.0757	6	4.3553	6	4.0538	6	3.7845
7	6.2303	7	6.0021	7	5.7864	7	4.8684	7	4.4923	7	4.1604
8	7.0197	8	6.7327	8	6.4632	8	5.3349	8	4.8820	8	4.4873
9	7.7861	9	7.4353	9	7.1078	9	5.7590	9	5.2285	9	4.7716
10	8.5302	10	8.1109	10	7.7217	10	6.1446	10	5.5364	10	5.0188
15	11.9379	15	11.1184	15	10.3797	15	7.6061	15	6.6329	15	5.8474
20	14.8775	20	13.5903	20	12.4622	20	8.5136	20	7.2414	20	6.2593
30	19.6004	30	17.2920	30	15.3725	30	9.4269	30	7.7664	30	6.5660
40	23.1148	40	19.7928	40	17.1591	40	9.7791	40	7.9281	40	6.6418
50	25.7298	50	21.4822	50	18.2559	50	9.9148	50	7.9778	50	6.6605
60	27.6756	60	22.6235	60	18.9293	60	9.9672	60	7.9932	60	6.6651
70	29.1234	70	23.3945	70	19.3427	70	9.9873	70	7.9979	70	6.6663
80	30.2008	80	23.9154	80	19.5965	80	9.9951	80	7.9994	80	6.6666
90	31.0024	90	24.2673	90	19.7523	90	9.9981	90	7.9998	90	6.6666
100	31.5989	100	24.5050	100	19.8479	100	9.9993	100	7.9999	100	6.6667

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1	1.03000	1	1.040	1	1.050	1	1.100	1	1.125	1	1.150
2	1.06090	2	1.082	2	1.103	2	1.210	2	1.266	2	1.323
3	1.09273	3	1.125	3	1.158	3	1.331	3	1.424	3	1.521
4	1.12551	4	1.170	4	1.216	4	1.464	4	1.602	4	1.749
5	1.15927	5	1.217	5	1.276	5	1.611	5	1.802	5	2.011
6	1.19405	6	1.265	6	1.340	6	1.772	6	2.027	6	2.313
7	1.22987	7	1.316	7	1.407	7	1.949	7	2.281	7	2.660
8	1.26677	8	1.369	8	1.477	8	2.144	8	2.566	8	3.059
9	1.30477	9	1.423	9	1.551	9	2.358	9	2.887	9	3.518
10	1.34392	10	1.480	10	1.629	10	2.594	10	3.247	10	4.046
15	1.55797	15	1.801	15	2.079	15	4.177	15	5.852	15	8.137
20	1.80611	20	2.191	20	2.653	20	6.727	20	10.545	20	16.367
30	2.42726	30	3.243	30	4.322	30	17.449	30	34.243	30	66.212
40	3.26204	40	4.801	40	7.040	40	45.259	40	111.199	40	267.864
50	4.38391	50	7.107	50	11.467	50	117.391	50	361.099	50	1083.657
60	5.89160	60	10.520	60	18.679	60	304.482	60	1172.604	60	4383.999
70	7.91782	70	15.572	70	30.426	70	789.747	70	3807.821	70	17735.72
80	10.6409	80	23.050	80	49.561	80	2048.400	80	12365.22	80	71750.88
90	14.3005	90	34.119	90	80.730	90	5313.023	90	40153.83	90	290272.3
100	19.2186	100	50.505	100	131.501	100	13780.61	100	130392.4	100	1174313

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n	P/F	n	P/F	n	P/F	n	P/F	n	P/F	n	P/F
1	0.9709	1	0.9615	1	0.9524	1	0.9091	1	0.8889	1	0.8696
2	0.9426	2	0.9246	2	0.9070	2	0.8264	2	0.7901	2	0.7561
3	0.9151	3	0.8890	3	0.8638	3	0.7513	3	0.7023	3	0.6575
4	0.8885	4	0.8548	4	0.8227	4	0.6830	4	0.6243	4	0.5718
5	0.8626	5	0.8219	5	0.7835	5	0.6209	5	0.5549	5	0.4972
6	0.8375	6	0.7903	6	0.7462	6	0.5645	6	0.4933	6	0.4323
7	0.8131	7	0.7599	7	0.7107	7	0.5132	7	0.4385	7	0.3759
8	0.7894	8	0.7307	8	0.6768	8	0.4665	8	0.3897	8	0.3269
9	0.7664	9	0.7026	9	0.6446	9	0.4241	9	0.3464	9	0.2843
10	0.7441	10	0.6756	10	0.6139	10	0.3855	10	0.3079	10	0.2472
15	0.6419	15	0.5553	15	0.4810	15	0.2394	15	0.1709	15	0.1229
20	0.5537	20	0.4564	20	0.3769	20	0.1486	20	0.0948	20	0.0611
30	0.4120	30	0.3083	30	0.2314	30	0.0573	30	0.0292	30	0.0151
40	0.3066	40	0.2083	40	0.1420	40	0.0221	40	0.0090	40	0.0037
50	0.2281	50	0.1407	50	0.0872	50	0.0085	50	0.0028	50	0.0009
60	0.1697	60	0.0951	60	0.0535	60	0.0033	60	0.0009	60	0.0002
70	0.1263	70	0.0642	70	0.0329	70	0.0013	70	0.0003	70	0.0001
80	0.0940	80	0.0434	80	0.0202	80	0.0005	80	0.0001	80	0.0000
90	0.0699	90	0.0293	90	0.0124	90	0.0002	90	0.0000	90	0.0000
100	0.0520	100	0.0198	100	0.0076	100	0.0001	100	0.0000	100	0.0000