Lifetime Energy Output vs. Lifetime Energy Investment: EROI

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Outline

The shortcomings of a purely economic assessment of energy technologies

Energy Payback Time vs. full lifetime energy cycle assessment

Definition and classic papers on Energy Return on (Energy) Invested: EROI

My re-examination of EROI data based on newer/additional data + technological insights

Electrical Power Plant EROI's (in order of supposedly decreasing EROI):

- Hydro / Wind / Coal / Natural Gas / Solar / Nuclear
- My dramatic revision of Wind and Nuclear EROIs based on their technology evolution

Fuel EROI's: Coal, Oil & Gas, Tar Sands, Oil Shale, Biofuels

- The murky world of biofuel EROI assessment,
  - where sound carbon footprint arguments can strongly color EROI evaluation

Final comparison of classic EROI values with my reassessed EROI numbers

(Written / Revised: October 2017)

Lifetime Energy Output vs. Lifetime Energy Investment: EROI

This group of note sets compares energy technologies in different ways

Starting with their land, water, and raw material requirements

And ending with an analysis of their present day economics

Some would say that economics **should** have the last word

Because Adam Smith's "invisible hand" will identify the most effective solutions

But as applied to energy, simple economics can overlook important facts such as:

1) Stable energy supply is just too damned important to a country!

Which inevitably leads to that government's massive market intervention

For instance, in the U.S. we now heatedly debate energy subsidies & tax breaks

Which we tend to associate with solar and wind energy

Despite fossil-fuel subsidies & tax breaks being much older & much larger

And massive subsidization is the worldwide NORM:

A 2015 International Monetary Fund report concluded that across the world:

Fossil fuels receive a $5.3 trillion annual subsidy = 6.5% of global GDP [1]

And this is hardly something new - Look back over the last century's world history:

German and Japanese WWII invasions were heavily motivated by fuel access

As were near continuous European & U.S. interventions in the Middle East

SIMPLE economics often further overlooks what economists themselves label:

2) "The Social Cost of Carbon" & "Negative Externalities"

Which is the idea that the market cost of energy does ≠ Its true cost

E.G., fossil fuel prices don't cover their true health & environmental costs

And that many impacted individuals have no say in those economic transactions

Both of which I explore in my note set: **Where Do We Go From Here?** (pptx / pdf / key)

1) IMF 2015: https://www.imf.org/external/pubs/ft/wp/2015/wp15105.pdf

And then there is the problem that:

3) Economics is largely about NOW (this quarter's profit or loss!)

Where sustainability is instead primarily about TOMORROW

But how can one anticipate tomorrow? One tool is **Life Cycle Analysis (LCA)**

Which, applied to energy, involves trying to evaluate a technology's impact:

BEFORE it comes into operation:

Including the impact of its raw materials, parts, construction . . . PLUS:

WHILE it is in operation:

Including the impact of its energy product, fuel, wastes, labor . . . PLUS:

AFTER is has ceased operation:

Including costs of "decommissioning," waste reclamation & storage . . .

In other words:

A Life Cycle Analysis attempts to evaluate the **complete impact**

that an action taken today will have upon a future world

Such a full and accurate evaluation will be extraordinarily complex

Leading researchers to sub-divide LCA into different categories

For energy, two of the most heavily researched categories are:

Life Cycle Analysis of Greenhouse Gas Emissions

Which I'll explore in my later note set on:

Greenhouse Effect, Carbon Footprint & Sequestration (pptx / pdf / key)

Life Cycle Analysis of Energy Input & Output

Which is the topic of this note set

*Research on **Energy Life Cycle Analysis** is surprisingly young*

Most examples I've found appeared well after the year 2000

And until about 2010, energy was mostly just part of much larger LCA analyses

Which typically evaluated dozens of parameters (differing from study to study)

The focus seemed to turn to energy only when doubts were raised by solar energy

Specifically, about solar's ability to **ever** produce more energy than it required

(As previewed in **Today's Photovoltaic Solar Cells** (pptx / pdf / key) notes)

The response was to define the parameter: **Energy Payback Time (EPBT)**

= The time an energy technology must operate in order to

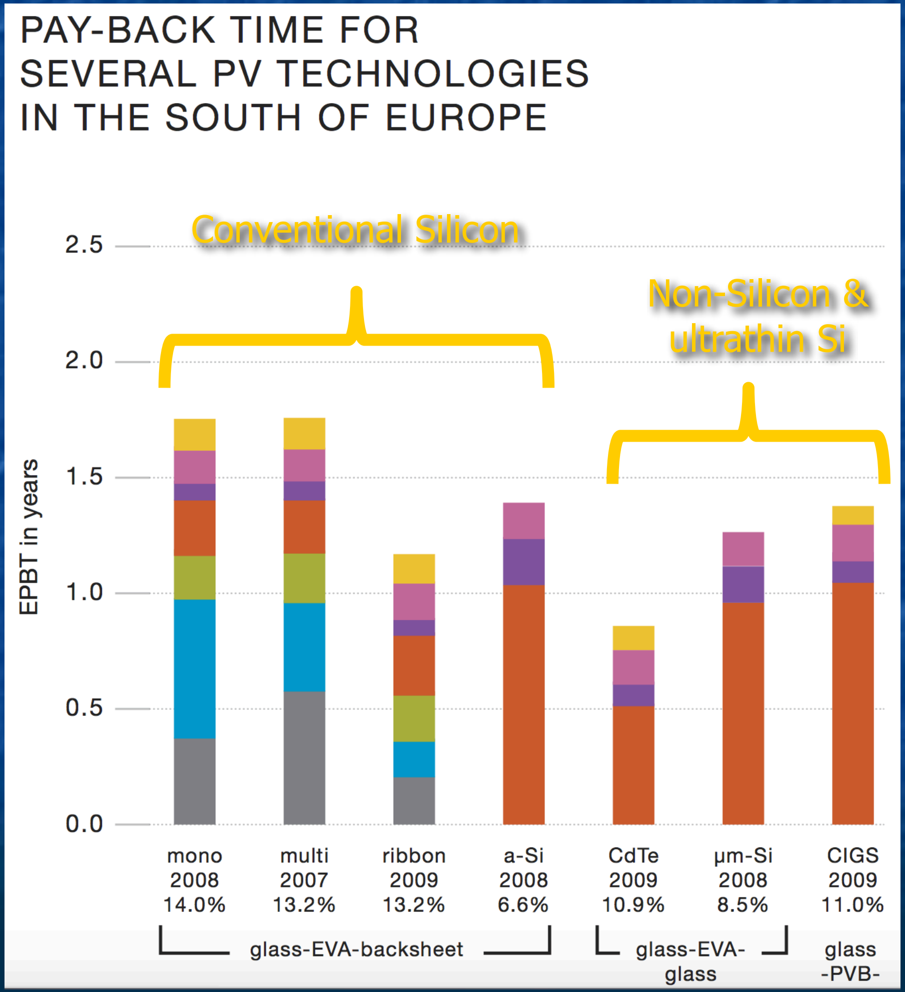
produce an amount of energy equivalent to all of the energy

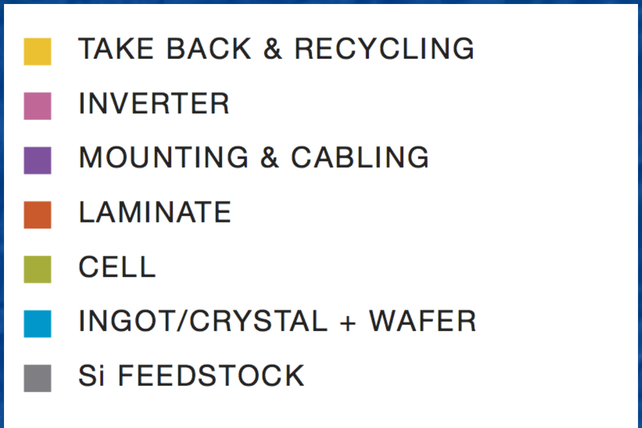
expended in its manufacture, operation and decommissioning

Here is an example of a solar energy EPBT study:

From a 2011 Greenpeace report [1] citing an International Energy Agency database [2]

(with my yellow annotations added)



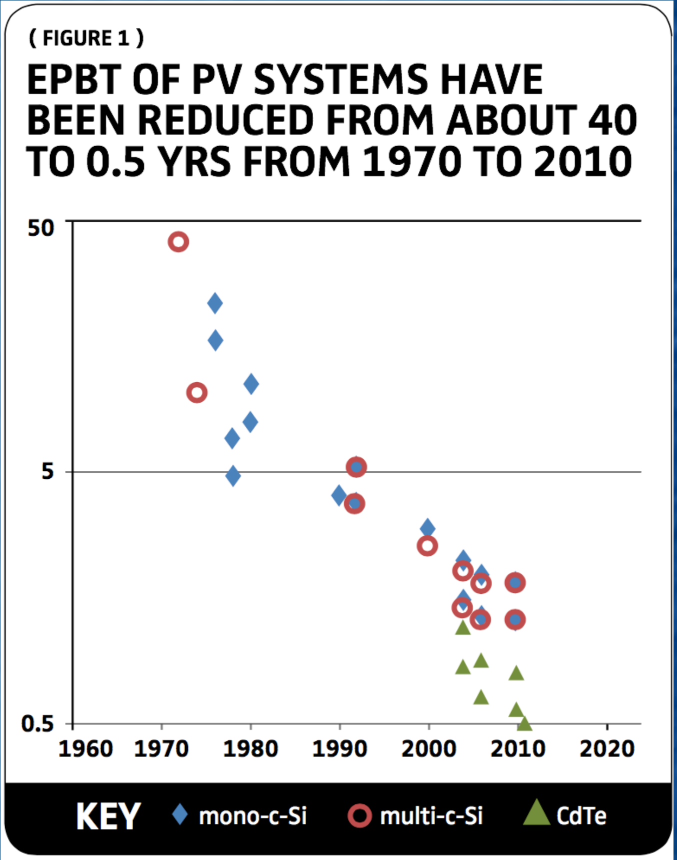


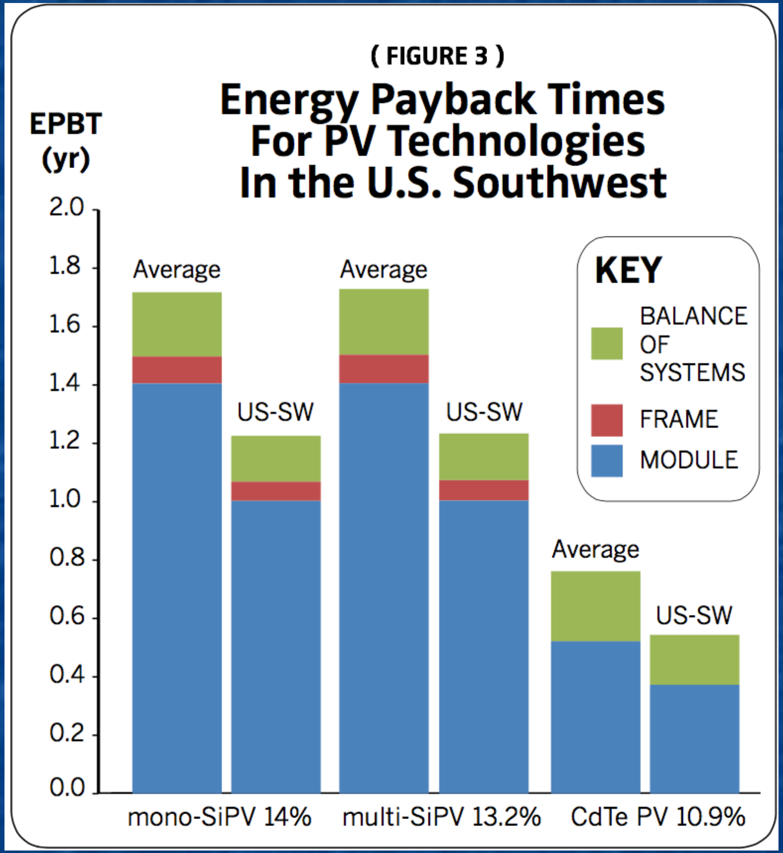
1) Greenpeace 2011 (page 84): http://www.greenpeace.org/international/Global/international/publications/climate/2011/Final%20SolarGeneration%20VI%20full%20report%20lr.pdf

2) IEA WEO; http://www.worldenergyoutlook.org/resources/energydevelopment/energyaccessdatabase/

But are you ready to trust Greenpeace?

Here, instead, is a study from the U.S. National Society of Professional Engineers:



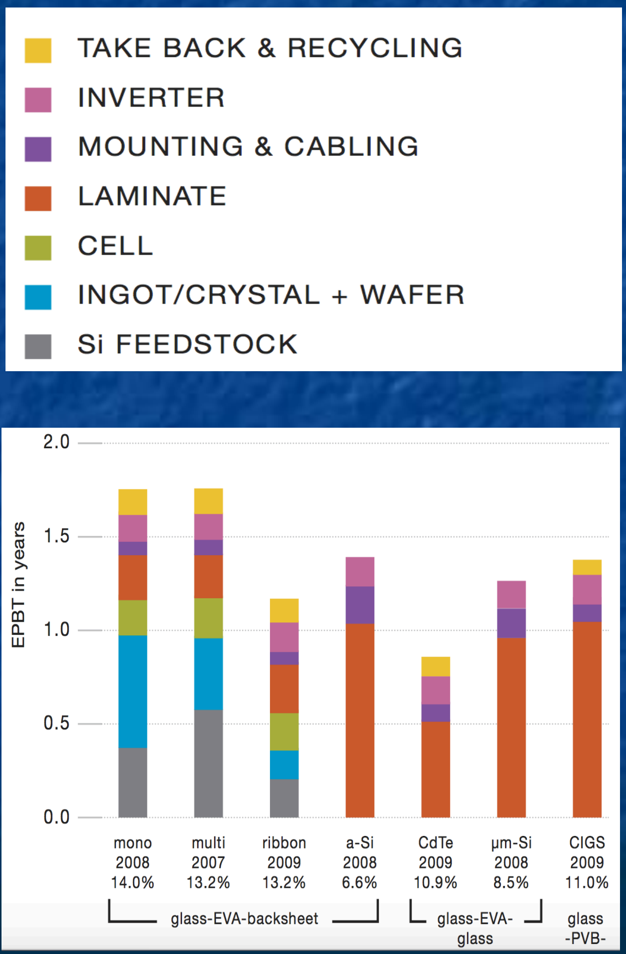


Fthenakis 2012) http://www.clca.columbia.edu/236_PE_Magazine_Fthenakis_2_10_12.pdf

The two studies are in surprisingly good agreement

So let's examine the first study in greater detail:

Colors identify how much energy was put into each stage of the solar cell's lifecycle:



In actual life cycle order:

Extracting & processing the raw Si "feedstock"

Converting it into large crystals, and then wafers

Manufacturing those wafers into solar cells

Laminating individual solar cells into a solar panel

Mounting and electrically connecting that panel

Building the circuit to "invert" the cell's natural low voltage DC into conventional grid AC power

Energy used in retiring & recycling this system

Trying to ***exploit*** *these data:*

EPBT = Energy put INTO these cells, so smaller EPBT is better, right?

That immediately suggests:

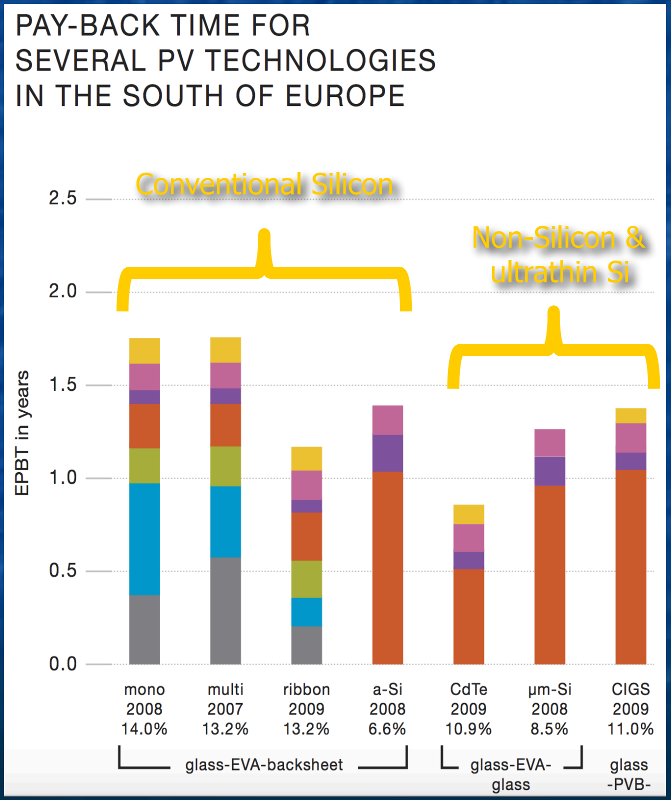
1) Avoid **Conventional Silicon** (Single crystal)

2) Choose instead cells made from either:

CIGS (Copper Indium Gallium Selenide)

um-Si (Micro/polycrystalline Si)

CdTe (Cadmium Telluride)



Would these indeed be your best choices?

Probably Not

Because Energy Payback Times alone are just too incomplete!

First, because they omit often critical technical information: [1]

Single crystal Si is the most technologically & commercially mature material

And it has one of the very highest energy conversion efficiencies

Whereas the EPBTs in the right group are low because they are "thin films"

Which means that they **do not** employ single crystals

Making them less stable and thus prone to decomposition

Which, for CIGS and CdTe, invites release of toxic materials

But is it really fair to critique EPBT's on technological details?

After all, they were only MEANT to evaluate energy impact!

1) For details see: **Today's Photovoltaic Solar Cells** (pptx / pdf / key) **Tomorrow's Solar Cells** (pptx / pdf / key)

Let me zero out almost all of those technological details

By assuming, temporarily, that all of those cell types are technologically equivalent

Except for one thing: **How long they will be able to generate power**

Yes, this derives from some of those technological details

But isn't it a blatantly obvious question, one that **any** consumer would ask?

Even if you hadn't a clue about how a car actually works,
wouldn't you seek an estimate of its lifetime from a trusted source?

For solar cell's, let me try to fill in as that hopefully trustworthy source:

Single crystal Si solar cells can produce power for over 20 years

This may fall to 10 years for microcrystalline Si solar cells

And may be as little as three years for today's CIGS solar cells

Combining this with the 1st study's EPBT data:

	EPBT	Energy Generation Lifetime
Single Crystal Si solar cells:	1.75 yrs	> 20 years
Microcrystalline Si Solar cells:	1.25 yrs	~ 10 years
CIGS thin film solar cells:	1.4 yrs	~ 3 years

After paying off its energy debt, Crystal Si cells produce energy for ~ 18 years

After paying off its energy debt, Microcrystal Si cells produce energy for ~ 9 years

After paying off its energy debt, CIGS cells produce energy for ~ 2 years

My lifetime estimates for Microcrystalline Si and CIGS may be somewhat inaccurate

But I think I've made my point:

EPBT alone provides a poor (dumb?) basis for making energy decisions

It makes more sense to consider a full energy "investment cycle"

Before making a **financial** investment, you'd want to know its likely ratio of:

Income Produced / Monetary Investment ~ Return on Investment (ROI)

A similar **energy** measure would be the ratio of:

Lifetime Energy Produced / Lifetime Energy Invested

For years researchers gave this (or its reciprocal) different names, including:

Energy Intensity

Energy Intensity Ratio

Energy Return on Invested

Energy Return on Investment

Energy Return on (energy) Invested

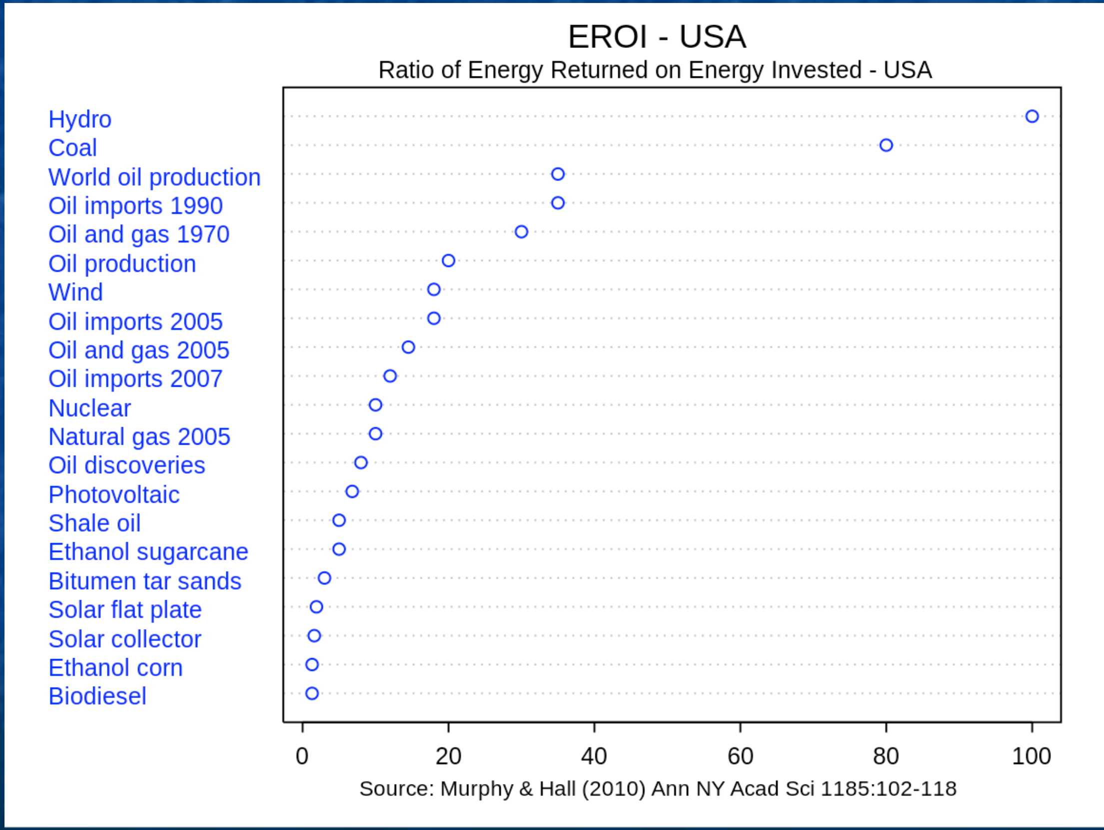
Energy Return on Invested Energy

But thankfully, they've now converged on the simple abbreviation: ***EROI***

Largely stimulated by the 2010 paper of D.J. Murphy & C.A.S. Hall entitled:

Year in Review: EROI or energy return on (energy) invested [1]

Wikipedia's plot of data from that seminal paper: [2]



1) Or as I will denote it: Murphy 2010 - Year in review: EROI or energy return on (energy) invested

2) Energy Return on Energy Invested, Wikipedia, https://en.wikipedia.org/wiki/Energy_returned_on_energy_invested

But if you make it past "Pay Walls" to actually ***read*** *that paper*

You'll find it's **mostly a discussion about the methodology** of EROI calculation:

EROI's numerator, **Lifetime Energy Produced**, is pretty easy to pin down

But its denominator, **Lifetime Energy Investment**, is far more difficult

First, given that many energy technologies operate for a half or even a full century,

one must be extremely careful not to **overlook** any energy input over that span

But which energy INPUTS should be included?

For instance, should we include the chemical energy intrinsic to a fuel?

Most researchers say no, arguing that we should focus on man's energy input alone

For fuels that is the energy we put into mining/drilling, refining & transporting it

EROI's calculated on that basis are sometimes called **external EROIs**

But there are subtleties in even "external EROI" calculation:

For instance, one must sniff out energy inputs lurking within raw materials

Such as the amount of energy put into the growth of Si solar cell crystals

Or into formulating the concrete used in massive nuclear & hydroelectric plants

And for fuels, what if some of that fuel is actually expended in the fuel's production?

As it is when sugar cane is burned as a part of ethanol's production process

Or when tar sand's oil extraction depends on heat from burning part of that oil

Or what if the byproduct of one fuel's production might supplant another fuel's use?

As when corn mash fermented to produce ethanol can be used as animal feed,

eliminating the energy otherwise needed for separate growth of feed plants

Or what about energy to repair roads, rails & pipelines **essential** for fuel transport?

And then there is the question of EROIs' larger significance:

Because, as with Energy Payback Times, by discussing **only** energy

EROI's provide a very incomplete picture of a technology's true viability

Leading many EROI research studies to extend their discussion into economics

Asking questions such as: **Is there a MINIMUM acceptable value of EROI?**

= An EROI below which economics too would almost certainly make no sense?

This is indeed discussed at length in Murphy & Hall's seminal EROI paper

With concludes that when the cost of economic "externalities" are included:

To succeed economically, a fuel's EROI must exceed ~ 3

But for all of their background and/or side discussion, I was surprised to find that:

EROI papers often include little to no primary data or discussion

They rely on secondary data, generally presented solely through one or two tables

And even when data are explained, it's done in just 1-2 meager sentences

The key data table
from Murphy & Hall's paper:

Resource	Year	Magnitude (EJ/yr)	EROI (X:1)	Reference
Fossil fuels				
Oil and gas	1930	5	>100	2
Oil and gas	1970	28	30	1, 4
Oil and gas	2005	9	11 to 18	2
Discoveries	1970		8	1, 4
Production	1970	10	20	1, 4
World oil production	1999	200	35	21
Imported oil	1990	20	35	32
Imported oil	2005	27	18	32
Imported oil	2007	28	12	32
Natural gas	2005	30	10	32
Coal (mine-mouth)	1950	n/a	80	2
Coal (mine-mouth)	2000	5	80	2
Bitumen from tar sands	n/a	1	2 to 4	32
Shale oil	n/a	0	5	32
Other nonrenewable				
Nuclear	n/a	9	5 to 15	32, 51
Renewables				
Hydropower	n/a	9	>100	32
Wind turbines	n/a	5	18	34
Geothermal	n/a	<1	n/a	32
Wave energy	n/a	<<1	n/a	32
Solar collectors				
Flate plate	n/a	<1	1.9	4
Concentrating collector	n/a	0	1.6	4
Photovoltaic	n/a	<1	6.8	52
Passive solar	n/a	n/a	n/a	32
Biomass				
Ethanol (sugarcane)	n/a	0	0.8 to 10	4, 53
Corn-based ethanol	n/a	<1	0.8 to 1.6	26
Biodiesel	n/a	<1	1.3	32

As an experienced physical scientist, I found this paucity of primary data unsettling

Especially given the intense controversy surrounding many EROI values!

Many studies ALSO lack clarity on a fundamental point:

What TYPE of "Lifetime Energy Produced" is being counted?

Is it electrical energy, kinetic energy, heat energy, chemical energy . . . ?

Counting "all of the above" can lead to immense confusion!

An example of such confusion? The hugely higher **FUEL** EROI's of Murphy & Hall

Can such fuels really be 10X more energy efficient than renewables?!!

No! **The preceding table is an "apples to oranges" comparison:**

For the fuels, at the top of the table, the energy output is **heat**

For for the bottom half of the table, the energy output is **electricity**

How then can their EROI's be compared? Going back to EROI's definition:

EROI = Lifetime Energy Produced / Lifetime Energy Invested

Correcting the EROI numerator:

Numerator: Lifetime Energy Out, here: Electrical Energy or Heat Energy

Many power plants CONVERT a fuel's heat output into electrical output

The EFFICIENCY of conversion can be evaluated for each plant, for example:

Coal-fired power plants convert heat to electricity at ~ 1/3 efficiency [1]

Yielding a way to translate EROI numerators:

$$\textbf{Energy}_{\text{ELECTRICITY}} = \textbf{Energy}_{\text{HEAT}} \times \textbf{Efficiency}_{\text{ELECTRICITY TO HEAT CONVERSION}}$$

Applying this to the "Lifetime Energy Out" numerator of an EROI:

Plant Electrical Energy Out = Fuel Heat Energy Out x Efficiency of Conversion

Using Murphy & Hall's Coal fuel EROI of 80, plus a conversion efficiency of ~ 1/3:

Coal Plant EROI => Coal Fuel EROI x (1/3)= (80)(1/3) ~ 27

But we're not done yet!

1) From my **FOSSIL FUELS** (pptx / pdf / key) note set

Correcting the EROI denominator:

Denominator = Lifetime Energy Input = All forms of energy EVER invested into:

A fireplace to produce heat: OR A power plant to produce electricity:

http://www.chroniclelive.co.uk/news/north-east-news/north-east-homes-burn-more-8690572

https://www.pakistantoday.com.pk/2016/06/08/pak-china-enter-into-agreement-for-coal-power-generation/

Even for the thousands of fireplaces required to match a plant's Coal consumption

Lifetime energy input for plant construction, operation & decommissioning

will almost certainly exceed the energy put into all of those fireplaces

Pulling Coal Plant EROI down even further from the Coal Fuel EROI

And thus making the last page's numerator-only correction a generous upper limit:

$$\textbf{EROI}_{\text{Electrical Plant}} \ll \textbf{EROI}_{\text{Plant's Fuel}} \times \textbf{Efficiency}_{\text{Heat of Electricity Conversion}}$$

With all of those observations, caveats, doubts and conversions in mind:

I'll now draw data from an array of well-recognized EROI studies

By subject, in order of increasing controversy (decreasing EROI)

Starting with electrical energy producing technologies

Ending with heat producing fuels

And true to the spirit of **WeCanFigureThisOut.Org**

I'll also search out my own independent data sources

Including, most importantly, **newer primary data sources**

And generate my own **independent analyses** of both old and new data

For information on my background, visit: https://wecanfigurethisout.org/ABOUT/About.php

To aid YOUR independent investigation:

You may want make use of the **very long** list of publications I'm about to discuss

My usual note set practice is to insert the URLs of my sources

But even I find URLs near impossible to remember and/or keep track of

Thus, in this note set, I'm going to switch to a more conventional citation format of:

first author + year + (immensely more understandable & memorable) title

But if you DO set out on an independent investigation (as you always should!)

I hope you've realized that my note sets have companion Resource Webpages

Which provide my categorized references, **along with URLs**,

and (where pay walls permit) **downloadable cached copies**

For this note set, that can all be found at this link: **EROI Resources Webpage**

Onward!

A particularly noteworthy review of EROI data was published in 2013

Its impact was exceptional both because it was published in Scientific American: [1]

The True Cost of Fossil Fuels, Mason Inman, April 2013, Scientific American

And because it was accompanied by a separate article discussing its methodology: [2]

Behind the Numbers on Energy Return on Investment, Inman

With the author additionally sharing his work with a pair of energy bloggers: [3]

Energy Return on Investment - Which Fuels Win?, Hope & Donald

1) Inman 2013a

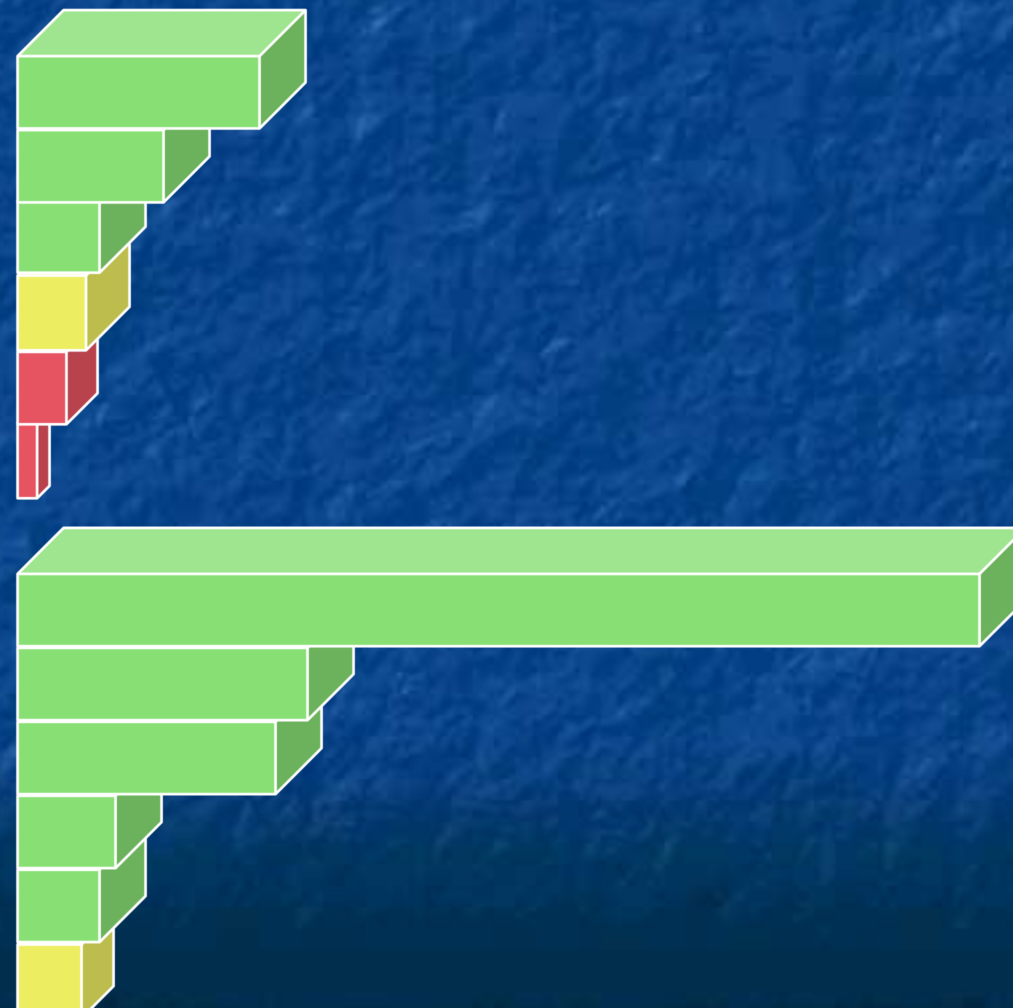
2) Inman 2013b

3) Hope 2013

My rendition of the data from those 2013 Scientific American articles:

Colors reflect articles' conclusion that economic viability requires EROI of at least **5**

Technology	EROI
Heat from:	
Conventional oil	16
Ethanol from sugarcane	9
Biodiesel from soy	5.5
Tar Sands	5
Heavy oil from California	4
Ethanol from corn	1.4
Electricity from:	
Hydroelectric Dams	40+
Wind	20
Coal	18
Natural Gas	7
Solar PV	6
Nuclear	5



Now digging deeper

(Which will lead to my very different EROI figure given at the end of this note set)

EROIs for Power Plant Electricity Generation

Electricity from Hydro

Hydro with Reservoir (Hoover Dam)

Run-of-the-River Hydro (Bonneville Dam)

Images via Google Earth

Hydro Power Plant EROI

Murphy & Hall's data table (shown above) gives hydro's EROI as: **>100**

Its reference, #32, which is not discussed in the text, cites a series of postings

to an online energy discussion forum with no obvious connection to hydro

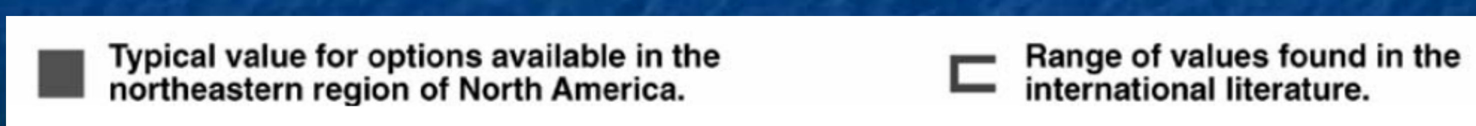
Inman, who was inspired by Murphy & Hall, cites instead the the work of Gagnon

Who in a 2002 paper mentions EROIs for both Quebec & international locations:

	Hydro w/ Reservoir:	Hydro Run-of-the-River:
Quebec:	**205**	**267**
International:	**50-260**	**35-267**

The 2002 Gagnon paper provides no correlation with hydroelectric plant size

More critically, it **cites no sources** beyond this note at the bottom of its data table:


Typical value for options available in the northeastern region of North America.

Range of values found in the international literature.

The first energy forum link) http://www.theoildrum.com/node/3412
Gagnon 2002) Life-cycle assessment of electricity generation options: The status of research in year 2001

However, I eventually found a later Gagnon paper:

Which, in 2008, DID finally include sources for hydro EROIs he'd called out in 2002

But when I tried to track them down, key sources turned out to be

from arguably non-objective sources (e.g., Hydro-Quebec),

and they were written (or at least titled) in only French

Moving on, I then found a 2015 study by Atlason & Unthorsson

Which **finally** provided a detailed EROI study of a **single** hydroelectric plant

Concluding that an **EROI of 110** was likely over its 100 year lifetime

But, located in Iceland, this plant may or may not have been typical

I next found the U.S. Department of Energy's 2016: **Hydropower Vision** which:

400+ pages long, called out "EROI" in its introductory table of acronyms

But only on page 306 briefly mentioned hydroelectric **EROI of up to 470**

Gagnon 2008) Civilisation and Energy Payback
Atalson 2015) Energy Return on Investment of Hydroelectric Power Generation Calculated Using a Standardised Methodology

But digging even deeper:

The DOE's **Hydropower Vision** gave as **its** source a 2011 paper by Kumar:

Which was actually Chapter 5 of the International Panel on Climate Change's

2011 Special Report on Renewable Energy Sources and Climate Change

But when I dug up that IPCC chapter

It's gave as **its** sources as the **same two papers by Gagnon**!

Thus, after digging up what first appeared to be a whole array of data sources,

from increasingly prestigious organizations, in increasingly long-winded reports

I ended up with data actually originating from ONLY TWO sources:

- One covering only a single hydro plant - but with the depth I had sought!

- The other based on possibly biased data, readable by only French speakers

My conclusion, based largely on the **absence** of dispute: **Hydro EROI ~ 100**

Kumar 2011) Chapter 5 – IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation

Electricity from Wind

Onshore Wind Farm:

http://www.telegraph.co.uk/news/earth/energy/windpower/12165896/Onshore-wind-farm-subsidies-could-continue-on-islands.html

Offshore Wind Farm

http://www.telegraph.co.uk/news/uknews/scotland/11155227/Four-offshore-wind-farms-approved-despite-deadly-impact-on-seabirds.html

Wind Farm EROI

In 2008 Lund cited sources such as a 1998 paper by White & Kulcinski to conclude:

Onshore wind EROI = 34, but more complex **Offshore wind EROI = 18**

In 2010 Murphy & Hall cited a then new work by Kubiszewski et al. to conclude:

All wind EROI = 18 (which Inman seemingly just rounded up to 20)

But I've come to believe a major oversight was committed:

Kubiszewski et al. correlated EROI with wind turbine power capacity

(Even if they made little use of this correlation in their paper's conclusion)

Here the **science of wind** is extremely important (see my **Wind Power** (pptx / pdf / key) notes):

Wind **speed** increases rapidly with height
+
Wind **power** increases as (wind speed) **Cubed**

→

Smaller numbers
of much taller turbines
produce **VASTLY** more power

White 1998: Net Energy Payback and CO2 Emissions from Wind Generated Electricity in the Midwest
Lund 2008: Review of the Application of Lifecycle Analysis to Renewable Energy Systems
Kubiszewski 2010: Meta analysis of EROI for Wind - Renewable Energy

The richness of the 2010 Kubiszewski meta-dataset:

Table 1
Metadata analysis of wind power systems.

Ref	Year of study	Location	Operational/ conceptual	EROI	CO_2 Intensity (gCO_2/kWh)	Power rating (kW)	Lifetime (yr)	Capacity factor (%)	Energy payback time (yr)	Analysis type	Scope as stated	Turbine information	On/off shore	Rotor diameter (m)	Hub height (m)	Wind speed (m/s)
[4]	1977	USA	c	43.5		1500	30	50.4		I/O	BCEMT	2 blades		60	50	10.5
[4]	1980	UK	c	12.5		1000	25	18.3		I/O	CM		on	46		18.4
[4]	1980	UK	c	6.1		1000	25	18.3		I/O	CM			46		18.4
[4]	1981	USA	o	1.0		3	20	26.8		I/O	CMO			4.3	20	10.1
[4]	1983	Germany	o	2.3		2	15	45.7		I/O	CM					
[4]	1983	Germany	o	3.4		6	15	45.7		I/O	CM					
[4]	1983	Germany	o	5.0		12.5	15	45.7		I/O	CM					
[4]	1983	Germany	o	8.3		32.5	15	45.7		I/O	CM					
[4]	1983	Germany	o	1.3		3000	20	45.7		I/O	CM	2 blades		100	100	
[4]	1990	Denmark	o	71.4		95	20	25.2		PA	M©	3 blades	on	19	22.6	
[4]	1990	Denmark	o	47.6	8.81	150	25	30.1		PA	M					
[4]	1990	Germany	o	32.3		300	20	28.9		PA	CMT	3 blades		32	34	11.5
[4]	1991	Germany	o	18.9		45	20	33.5		PA	M			12.5		
[4]	1991	Germany	o	32.3		225	20	39.9		PA	M			27		
[4]	1991	Germany	c	27.0		300	20	39.9		PA	M			32		
[4]	1991	Germany	c	22.2		3000	20	34.2		PA	M			80		
[4]	1991	Germany	o	11.8		30	20	14.4		PA	CGMOT	2 blades		12.5	14.8	13
[4]	1991	Germany	o	20.4		33	20	29.4		PA	M	2 blades		14.8	22	11
[4]	1991	Germany	o	14.7		95	20	20.5		PA	CGMT	3 blades	on	19	22.6	
[4]	1991	Germany	o	19.6		95	20	20.5		PA	M	3 blades		19	22.6	
[4]	1991	Germany	o	16.7		100	20	20.9		PA	M	2 blades		34	24.2	8
[4]	1991	Germany	o	20.4		150	20	25.6		PA	M	3 blades		23	30	13
[4]	1991	Germany	o	27.0		165	20	23.2		PA	M	3 blades		25	32	13.5
[4]	1991	Germany	o	18.9		200	20	21		PA	M	3 blades		26	30	13
[4]	1991	Germany	o	15.6		265	20	19		PA	M	2 blades		52	30.5	8.5
[4]	1991	Germany	o	20.8		450	20	20		PA	GM	3 blades		35	36	18
[4]	1991	Germany	o	15.4		3000	20	30.4		PA	GM	2 blades		100	100	12
[4]	1991	Japan	o	4.0	71.7e	100	20	31.5		I/O	CMT					
[4]	1992	Germany	o	11.2		0.3	20	38.8		PA	CDMOT	3 blades		1.5	11.6	9
[4]	1992	Germany	c	37.0		300	20	41.9		PA	CDGMOT	3 blades		32	34	
[4]	1992	Japan	o	2.9	95.6e	100	20	31.5		I/O	CMOT					
[4]	1992	Japan	o	30.3	33.7	100	30	28		I/O	CMOT			30		13
[4]	1992	Japan	o	18.5		100	30	40		I/O	CMOT	1983		30		10
[4]	1993	Germany	o	21.7	11e	300	20	22.8		PA	CDMOT					
[4]	1994	Germany	o		18.2e	500	20	27.4		I/O	CM					
[4]	1994	Germany	o	45.5		300	20	22.8		PA	MO(D)					
[4]	1994	Germany	o	14.7	8.1	500	20	36.5		PA	M	2/3 blades		39	41	
[4]	1995	UK	o	23.8	9.1	350	20	30		PA	M	3 blades		30	30	15
[4]	1996	Switzerland	o	3.1	52	30	20	7.9		PA	CDGMOT	2 blades		12.5	22	11.4
[4]	1996	Switzerland	o	5.0	28	150	20	7.6		PA	CDGMOT	3 blades		23.8	30	
[4]	1996	Germany	o		14e	1000	20	18.5		PA	CMO	3 blades		54	55	
[4]	1996	Germany	o		22e	1000	20	18.5		I/O	CMO	3 blades		54	55	
[4]	1996	UK	o		25	6600	20	29		I/O	CDMO					
[4]	1996	Japan	o	2.3	123.6e	100	30	20		I/O	CMO					
[4]	1996	Japan	o	2.2	123.7e	100	20	18		I/O	CMO	1984		30		
[4]	1996	Japan	o	5.8	47.4e	170	20	22.5		I/O	CMO			27		
[4]	1996	Japan	o	8.5	34.9e	300	20	18		I/O	CMO			28		
[4]	1996	Japan	o	11.4	24.1e	400	20	18		I/O	CMO			31		
[4]	1996	Germany	o	8.3	17	100	20	31.4		PA	CMO	3 blades		20	30	
[4]	1996	Germany	c	28.6	10	1000	20	36.2		PA	CMO	3 blades		60	50	
[4]	1997	Denmark	o	8.3		15	20	20.5		I/O	CMO	1980		10	18	
[4]	1997	Denmark	o	8.1		22	20	19.9		I/O	CMO	1980		10.5	18	
[4]	1997	Denmark	o	10.0		30	20	19		I/O	CMO	1980		11	19	
[4]	1997	Denmark	o	15.2		55	20	20.6		I/O	CMO	1980		16	20	
[4]	1997	Denmark	o	27.0		600	20	26.5		I/O	BCDEGMOT	3 blades		47	50	15

(continued on next page)

Scope as stated	Turbine information	On/off shore	Rotor diameter (m)	Hub height (m)	Wind speed (m/s)
CMO	3 blades	off	64	55	17
M(O)					
CMT(O)					
CMT(O)					
CMT(O)					
CGMOT	3 blades		40.3	44	
CGMOT	3 blades		40.3	44	
CGMOT	3 blades		66	67	
CGMOT	3 blades		66	67	
CDGMOT			66	67	
CDGMOT	E-66		66	67	
(B)CDMOT	Kenetech KVS-33	on	32.9	36.6	
(B)CDMOT	Tacke 600e	on	46.0	60.0	6.1
(B)CDMOT	Zond Z-46	on	46.0	48.5	
MTCGOD	3-blades	off	39	40.5	16
MTCGOD		on		41.5	
MCO					
DM(O)					
DM(O)					
CMT			30	30	
CGMOT	3 blades; E-40		40.3	44	
TCO					
MCTOD					
MCTOD					
MCTOD					
MTCOD	Enercon E-40	on	40.3	44	7.5
MTCOD	Enercon E-40	on	40.3	55	7.5
MTCOD	Enercon E-40	on	40.3	55	7.5
MTCOD	Enercon E-40	on	40.3	55	7.5
MTCOD	Enercon E-40	on	40.3	65	7.5
MTCOD	Enercon E-40	on	40.3	44	7.5
MTCOD	Enercon E-40	on	40.3	55	7.5
MTCOD	Enercon E-40	on	40.3	55	7.5
MTCOD	Enercon E-40	on	40.3	55	7.5
MTCOD	Enercon E-40	on	40.3	65	7.5
MTCOD	Enercon E-40	on	40.3	44	7.5
MTCOD	Enercon E-40	on	40.3	55	7.5
MTCOD	Enercon E-40	on	40.3	55	7.5

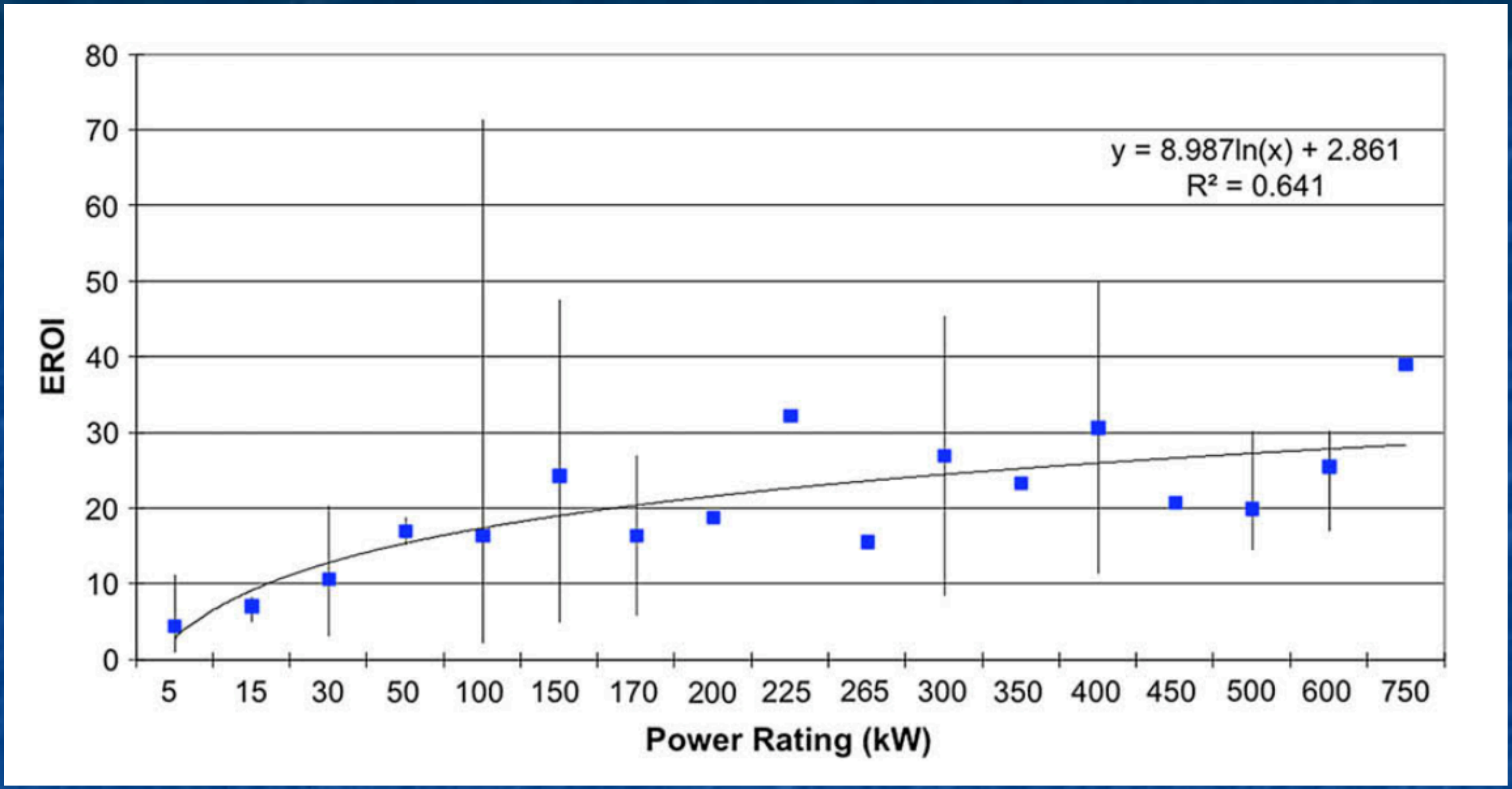
Ref	Year of study	Location	Operational/ conceptual	EROI	CO_2 Intensity (gCO_2/kWh)	Power rating (kW)	Lifetime (yr)	Capacity factor (%)	Energy payback time (yr)	Analysis type	Scope as stated	Turbine information	On/off shore	Rotor diameter (m)	Hub height (m)	Wind speed (m/s)
		Brazil														
[25]	2004	Germany and Brazil	c	15.6	13	500				PA-I/O	MTCOD	Enercon E-40	on	40.3	55	7.5
[25]	2004	Germany and Brazil	c	16.4	12	500				PA-I/O	MTCOD	Enercon E-40	on	40.3	65	7.5
[25]	2004	Brazil	c	32.7	3	500				PA-I/O	MTCOD	Enercon E-40	on	40.3	44	7.5
[25]	2004	Brazil	c	30.0	3	500				PA-I/O	MTCOD	Enercon E-40	on	40.3	55	7.5
[25]	2004	Brazil	c	24.0	3	500				PA-I/O	MTCOD	Enercon E-40	on	40.3	55	7.5
[25]	2004	Brazil	c	18.9	4	500				PA-I/O	MTCOD	Enercon E-40	on	40.3	55	7.5
[25]	2004	Brazil	c	18.9	4	500				PA-I/O	MTCOD	Enercon E-40	on	40.3	65	7.5
[25]	2004	Brazil	c	40.0	2	500				PA-I/O	MTCOD	Enercon E-40	on	40.3	44	7.5
[29]	2006	Italy	o	19.2	14.8e	7260	20			I/O	MTCOD		on	50	55	
[30]	2006	Germany	c	30.0	10.2	1500					MTCOD					
[30]	2006	Germany	c	32.7	8.9	2500					MTCOD					
[30]	2006	Germany	c	29.4	10.2	1500					MCOTD		on			
[30]	2006	Germany	c	32.3	8.9	2500					MCOTD		off			

Rotor diameter (m)	Hub height (m)	Wind speed (m/s)
).3	55	7.5
).3	55	7.5
).3	55	7.5
).3	65	7.5
26.5	95	9.2
).3	44	
).3	55	
).3	65	
5	67	
5	67	
5	67	

Notes: I/O = Input–output-based analysis, PA = Process analysis, c = conceptual, o = operating, B = Business management, M = Manufacture, T = Transport, C = Construction, G = Grid connection, O = Operation and maintence, D = Decommissioning, e = CO_2 equivalents including CH_4 and N_2O, () = partly covered.

Kubiszewski 2010: Meta analysis of EROI for Wind - Renewable Energy

Which facilitated their correlation of EROI with turbine power rating:



Small turbines at left (obsolete by 2010) => Wind EROI's of 5-20

versus

Almost 1 MW turbines at right (then modern) => Wind EROI's of 30-40

Kubiszewski 2010: Meta analysis of EROI for Wind - Renewable Energy

Wind energy industry sources recognized the significance of this trend:

As in an editorial posted in 2013 by the American Wind Energy Association [1]

But even their discussion has now become very dated because:

Today's wind farms are now built around 4 MW turbines

And 6 MW turbines are planned for new farms

I was not able to find a post-2013 wind EROI study reflecting these developments

But based on **straight-forward wind science** it is virtually certain

that modern much taller/larger turbines will achieve much higher EROIs

Leading me to PREDICT that for TODAY's much larger wind turbines:

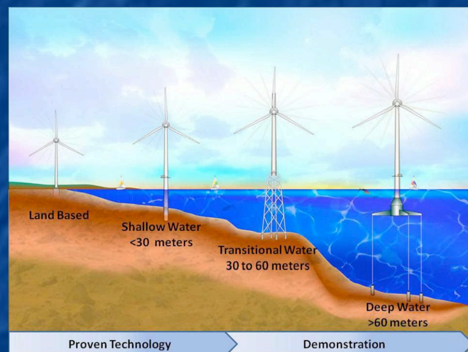
Onshore Wind EROI ≥ 40 (perhaps even substantially greater)

1) AWEA 2013: Setting the Record Straight about Wind's Lifecycle Emissions and Return on Energy Invested

As to offshore wind:

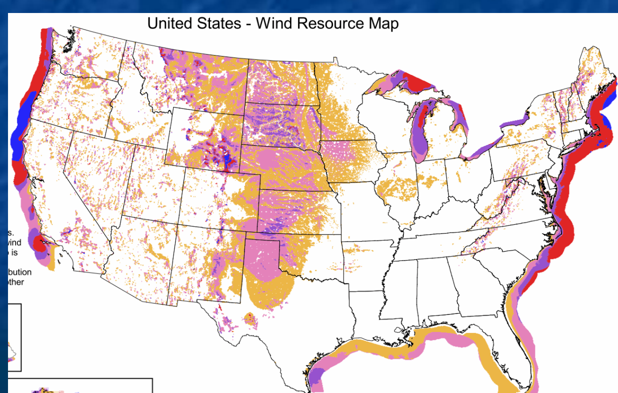
It is so much newer that I did not find convincing Offshore Wind EROI data

Its technology IS substantially more complex, as is its installation:



But offshore wind is also **much more** intense and **much less** intermittent:

Advantages amplified by wind power being proportional to wind speed cubed



Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m^2	Wind Speed[a] at 50 m m/s	Wind Speed[a] at 50 m mph
3	Fair	300 - 400	6.4 - 7.0	14.3 - 15.7
4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
5	Excellent	500 - 600	7.5 - 8.0	16.8 - 17.9
6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7
7	Superb	800 - 1600	8.8 - 11.1	19.7 - 24.8

[a] Wind speeds are based on a Weibull k value of 2.0

Suggesting offshore wind EROI **might** eventually match or exceed onshore EROI

Please see my **Wind Power** (pptx / pdf / key) note set for details and figure credits

Electricity from Coal

Photo purchased from: ungnoilookjeab via 123RF.com

Coal Power Plant EROI

In their seminal paper Murphy & Hall report **Coal EROI = 80**

But this is for HEAT ENERGY output and not ELECTRICAL ENERGY output

In 2012 Raugei, citing German language sources, gave Coal $EROI_{HEAT}$ ~ 40 - 80

He then multiplied this by a **heat-to-electricity-conversion-efficiency**

=> **Coal $EROI_{ELECTRICAL}$ = 12.2 - 24.6** (w/o EROI denominator correction!)

In 2013 Weissbach cited Spath's 1999 NREL report, and a German language source

to conclude **Coal $EROI_{ELECTRICAL}$ = 29 - 31**

Inman took his **Coal $EROI_{ELECTRICAL}$ = 18** value from the middle of Raugei's range

But these sources (and EROI's) ignore the impacts of coal pollution

Assuming, perhaps, that coal's swift decline would soon make it irrelevant?

Raugei 2012: Energy Return on Energy Investmen of Photovoltaics: Methodology & Comparisons with Fossil Fuel Life Cycles
Weisbach 2013 Energy Intensities EROIs and Energy Payback Tmes of Electricity Generating Power Plants

That pollution prompted major changes in coal power plant design:

As described in my FOSSIL FUELS (pptx / pdf / key) note set, there are now:

- Quickly declining, essentially uncontrolled and heavily polluting, coal plants
- Less polluting **integrated gasification** and/or **combined cycle** coal plants
- Hopes (pipe dreams?) of "clean coal" plants with full carbon sequestration

But **pollution controls** not only alter coal's heat-to-electricity-conversion-efficiency

Their added technology also contributes to lifetime energy input

Gagnon's 2008 review was one of few clearly recognizing this change, as it used

a 1999 NREL report by Spath, and a 2003 IEA report by Gielen

to compute a **Combined Cycle Coal EROI $_{\text{ELECTRICAL}}$ = 2.5 - 5**

I didn't find an EROI for full "integrated gasification + combined cycle" coal plants

(But an one might be calculable from Gielen's discussion of IGCC)

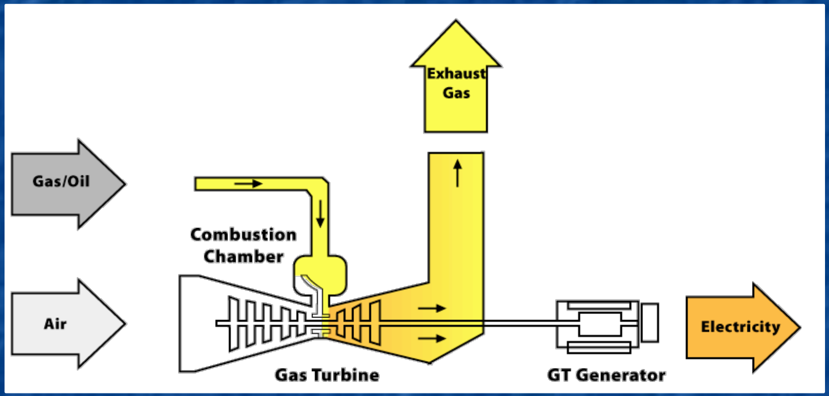
Gagnon 2008) Civilisation and Energy Payback

Spath 1999: Life Cycle Assessment of Coal-fired Power Production

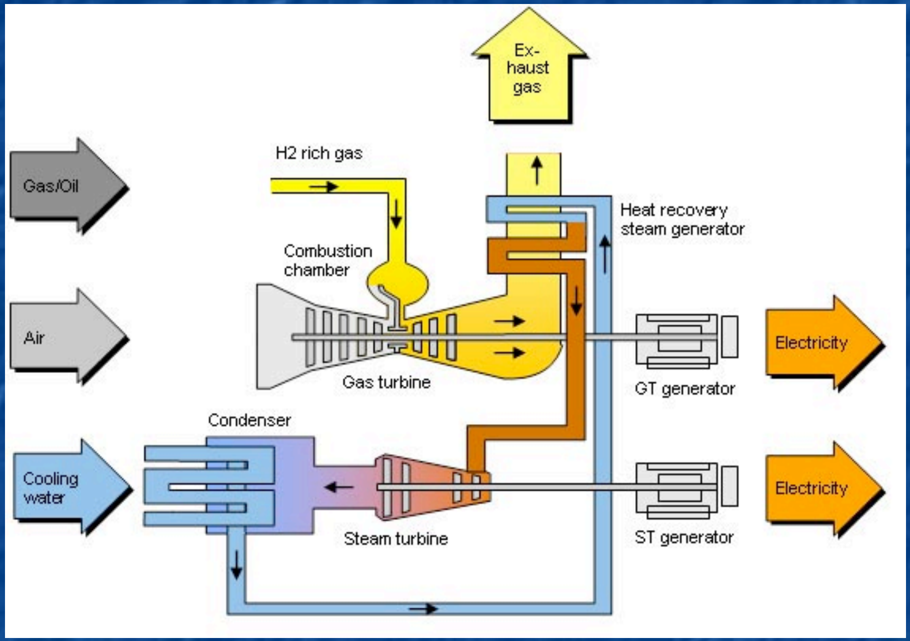
Gielen 2003: Future Role of CO2 Capture in the Electricity Sector

Electricity from Natural Gas (NG)

Open Cycle Gas Turbine (OCGT):



Combined Cycle Gas Turbine (CCGT):



https://www.consumersenergy.com/content.aspx?id=1345

http://www.power-technology.com/projects/uskmouth/uskmouth2.html

Gas Power Plant EROI

Murphy & Hall reported a **NG EROI = 10**, but they group it with Coal's 80

Suggesting that this is also natural gas's EROI for HEAT ENERGY output

But it **is** very close to Inman's **NG EROI $_{ELECTRICAL}$ = 7** which he got converting

a NG $EROI_{HEAT}$ value of 40 (from an unidentified source) and multiplying it

by a "typical" 40-45% NG heat-to-electricity-conversion-efficiency

(But making no correction for the change in Lifetime Energy Input!)

My FOSSIL FUELS note set instead identified OCGT NG plant efficiencies as ≤ 40%

Versus CCGT NG plant efficiencies in the low 60% range

Inman corroborated his calculation via King's 2010 "energy intensity" data

But King merged energy with economic supply & demand considerations

in a way that left me uneasy about their full equivalence to EROI's

King 2010: Energy intensity ratios as net energy measures of United States energy production and expenditures

More straightforward were reports such as:

Gagnon's 2008 paper, based on Spath's 2000 study of combined cycle gas turbines

Not to be confused with Spath's 1999 NREL study of coal-fired power plants!

Gagnon concluded that:

CCGT NG EROI $_{\text{ELECTRICAL}}$ = 2.5 if plant's NG sources were 4000 km distant

CCGT NG EROI $_{\text{ELECTRICAL}}$ = 5 if NG sources were substantially closer

In 2013 Weissbach, also clearly taking power plant technology into account

Reported a similarly low **CCGT NG EROI $_{\text{ELECTRICAL}}$ = 3.5**

Consideration of power plant technology makes these studies far more credible!

But with such abysmally low EROIs, how can NG be thriving in the US?

Gagnon 2008) Civilisation and Energy Payback

Spath 2000: Life Cycle Assessment of Natrual Gas Combined-Cycle Power Generation System

Weisbach 2013 Energy Intensities EROIs and Energy Payback Tmes of Electricity Generating Power Plants

Possible explanations for NG's prosperity in the U.S.

Turbine EROI's are likely eroded by their use of ultrahigh temperature titanium alloys

which increase the "Lifetime Energy Input" denominator of their EROI

(Mirroring the way single crystal Si PV EROI's are pulled down)

Nevertheless, they may still be chosen because Combined Cycle Gas Turbine plants

have a substantially lower carbon footprint than alternative coal power plants

But I suspect the real reason is instead that:

U.S. natural gas plants are now mostly used for **only** one or two evening hours,

adding power to the grid when consumption peaks (= "peaking power")

For such largely idle plants, low turbine capital cost becomes all important

Demonstrating a disconnect between low **economic** cost and high **energy** cost!

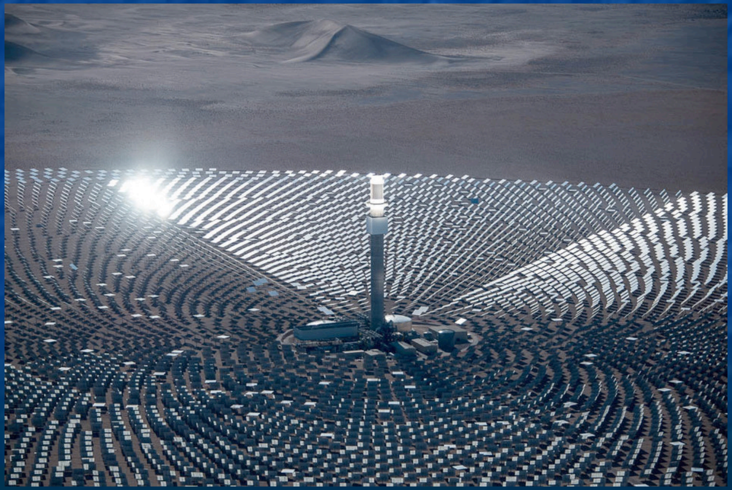
Electricity from Solar

Photovoltaic Solar Farm
(Topaz, California)

https://techxplore.com/news/2014-11-world-largest-solar-farm-california.html

Solar Thermal **Tower + Heliostats**
(Crescent Dunes, Nevada)

Solar Thermal **Trough Concentrators**
(Quarzazate, Morocco)



http://www.prnewswire.co.uk/news-releases/solarreserves-crescent-dunes-solar-energy-project-with-us-developed-storage-technology-receives-up-to-78-million-investment-from-capital-one-610901895.html

http://www.vilferelectric.com/en/2016/01/14/complejo-ouarzazate-planta-termosolar-nord-marruecos/

Solar Farm EROI:

Murphy and Hall's table does not clearly distinguish between

thermal vs. photovoltaic solar plants

nor between the many different types of photovoltaic cells

Instead just reporting **Solar PV EROI = 6.8**

Inman acknowledges the diversity of PV and its rapidly increasing EROIs

He cites Raugei's 2012 study which gives EROIs for various PV technologies as

single crystal Si = 6, multi-crystal Si = 6, Si ribbon = 9.5, CdTe = 11.8

But summarizes these as **Solar PV EROI = 6** (consistent w/ crystal Si PV)

These EROIs values are very close to his estimated boundary of economic viability!

Thus, as EPBT numbers did, they have fueled already intense public debate

Raugei 2012: Energy Return on Energy Investmen of Photovoltaics: Methodology & Comparisons with Fossil Fuel Life Cycles

This debate is mirrored within the EROI research community

As in their lingering discussion of methodology (see, for instance, Carbajales)

But unresolved technological questions may be even more important, such as:

Under intense UV sunlight, what is the lifetime of a PV technology?

And, during that lifetime, how will its power output likely decline?

For younger PV technologies such as CIGS, there is very little real-world data,

and virtually NO real-world data for research PV stars such as Perovskites

But data on mature technologies (based on Si, GaAs & CdTe) **are** known

Further, intense interest in PV has stimulated a wealth of recent EROI research

But rather than burrowing into that long list of recent EROI studies,

it makes more sense to jump to their cumulative bottom line via this:

Carbajales 2015: Energy Return on Investment (EROI) of Solar PV: An Attempt at Reconciliation

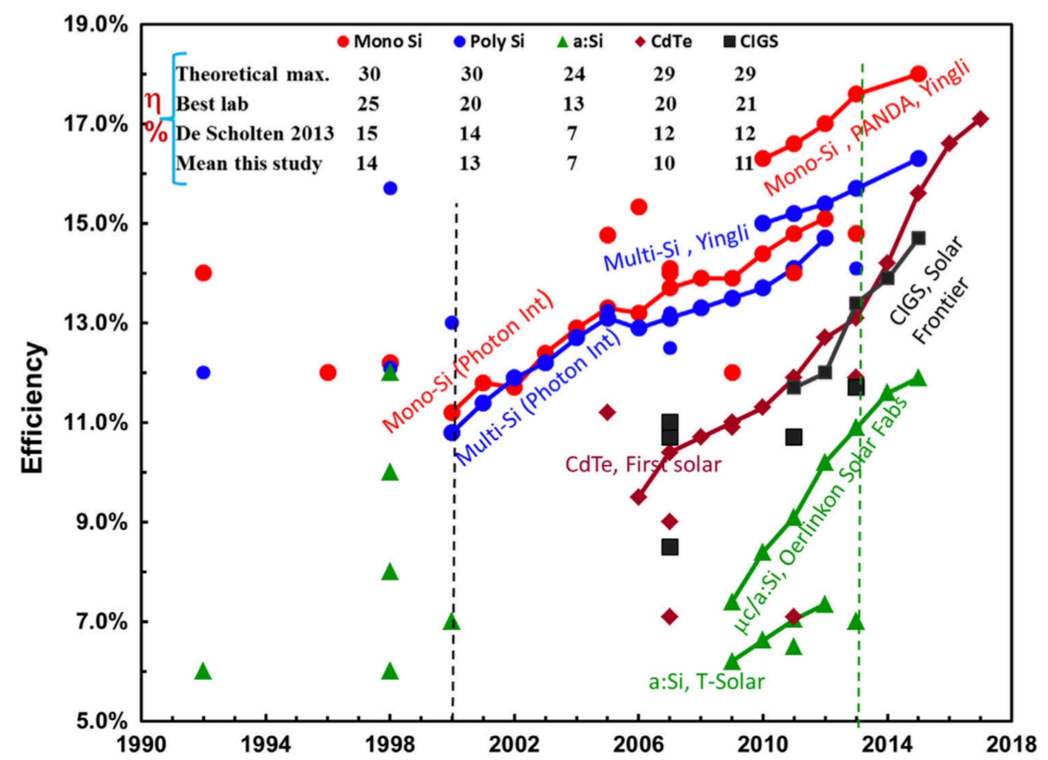
Meta-data analysis of 232 peer-reviewed PV EROI studies:

As presented in a 2015 Bhandari et al. paper that paid exceptional attention to

both technology-specific lifetimes and degradation patterns,

and to differing data credibility and confidence levels

That technology sensitivity can be seen in their plot of evolving solar PV efficiencies:



Bhandari 2015: Energy Payback Time and Energy Return on Investment of solar PV Systems: A Systematic Review and Meta-Analysis

Based on that sensitivity . . .

This group did **not** just average data from its 232 contributing studies

Instead, each of those papers was examined and compared in detail

Resulting in both a down-selection of sources and weighting of their data

Leading to these composite results:

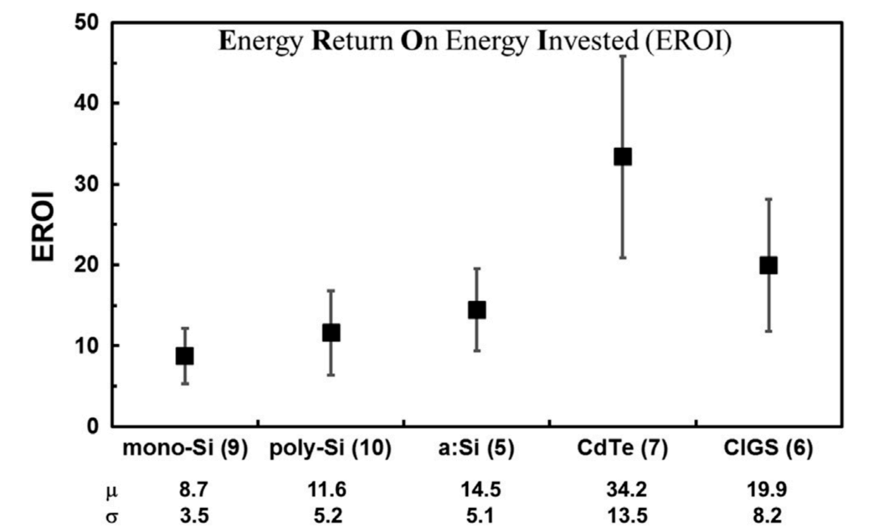


Fig. 7. Mean harmonized EROI with error bars representing one standard deviation. The number of values for each module type is included in parentheses. Mean (μ) and standard deviation (σ) are shown at the bottom of the graph.

EROI Means:

Mono-crystalline Si PV = 8.7

Poly-crystalline Si PV = 11.6

Amorphous Si PV = 14.5

CdTe PV = 34.2

CIGS PV = 19.9

NOTE: These composite 2015 values are 50-200% HIGHER than Raugei's 2012 results!

*But what about solar **thermal** power?*

The output of a **solar photovoltaic plant** is proportional to sunlight intensity

But the output of a **solar thermal plant** is NOT!

This stems from its functional resemblance to coal & nuclear power plants

all of which heat water past its boiling point, producing steam to drive turbines

Getting water TO its boiling point takes a lot of time and energy!

Which is why 19th century locomotives took **hours** to "get their steam up"

But this means that one should never turn a steam-driven power plant OFF

Because then all of that painfully acquired heat energy is allowed to dissipate

For this reason, whenever possible, coal and nuclear power plants run 24/7

and are thus dedicated to providing the Grid's unvarying "base" power

But solar thermal plants operate intermittently

Obviously loosing their sunlight power source every night

But also loosing much of that power source with every passing cloud

But where halving sunlight halves the power output of a solar PV plant

Halved sunlight can **completely shut down** a solar thermal plant

As can even the brief passage of particularly dark clouds

Why? Because if sunlight intensity falls far enough, or for long enough:

The plant's water (or oil) may no longer reach its boiling point,

leaving you with an effectively useless hot liquid!

Solar thermal power plants are thus uniquely vulnerable to **solar intermittency**

And their EROIs thus vary radically with their "capacity factor"

Which is their: (Actual energy output) / (Output under full sunlight)

~ the fraction of daytime they are fully illuminated

This has all sorts of weird consequences including:

- Some even fairly new solar thermal plants, such as California's Ivanpah,

  must kick-start themselves **every morning by burning natural gas**

- Tower + heliostat plants can slightly outperform trough concentrator plants

  Because "heliostat" mirrors can be steered toward cloud-free parts of the sky

These and other complications sharply elevate solar thermal's **economic cost**,

limiting solar thermal development to just a handful of plants worldwide,

mostly new and still experimenting with different design configurations

Myriad options also greatly complicate calculation of solar thermal **energy cost**

As can be seen in Larrain's 2012 attempt at calculating EROIs for solar plants

using different technological options, in different weather zones

Larrain 2102: Net Energy Analysis for Concentrated Solar Power Plants in Northern Chile

*However, solar thermal plants can also **store** energy*

At least if they use two fluids, one fluid heating the second fluid to boiling

And if that first fluid is a molten salt which can absorb a LOT of energy!

Indeed, molten salts can absorb **so much energy** that solar thermal plants might

continue boiling water for 6, 9, or even 12 hours after they loose sunlight

and thus continue producing power through cloudiness and nightfall

Which could make solar thermal the first really practical 24/7 renewable

Which is a BIG DEAL given that, as discussed in my PLANT ECONOMICS note set:

It costs as much to **store** solar PV and wind energy as it costs to make it!

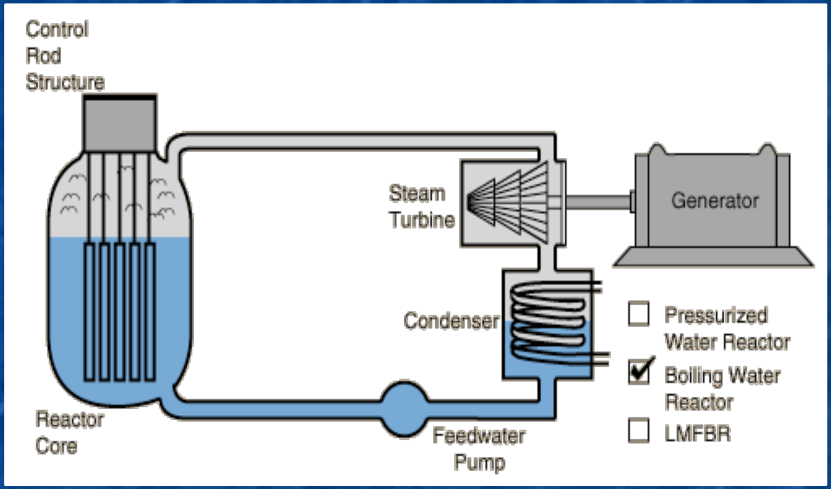
But with these unsettled & untested options, firm solar thermal EROI's don't yet exist

To further explore this subject, I suggest reading Ted Trainer's paper:

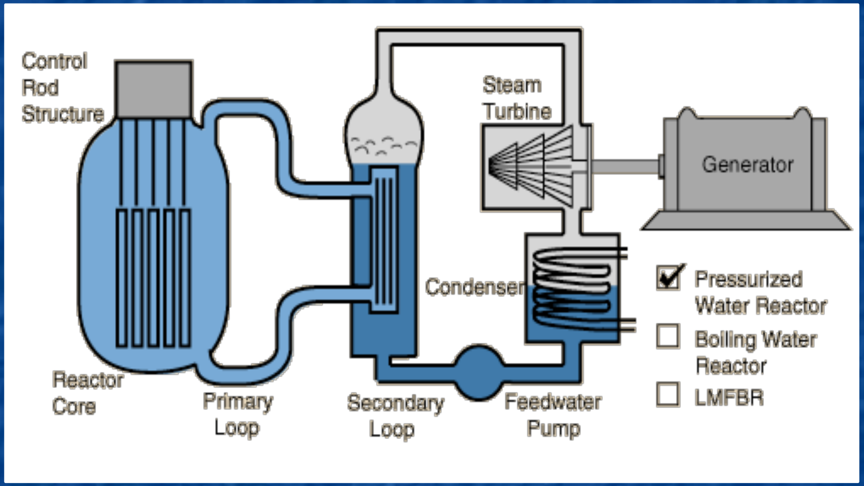
Limits to Solar Thermal Electricity, Renewable Energy 41, 123-33 (2014)

Electricity from Nuclear

Boiling Water Reactors (BWR):



Pressurized Water Reactors (PWR):



The dominant types of "light-water" (enriched uranium fueled) nuclear reactor

http://hyperphysics.phy-astr.gsu.edu/hbase/nucene/reactor.html

Nuclear Power Plant EROI

It will come as no surprise that Nuclear EROI's are intensely controversial

With the intensity of debate sometimes approaching hysteria

For instance, while investigating recent suspensions of nuclear plant construction

I found recurring discussion of an "Investment Watch" article entitled:

FALLING EROI KILLS WESTINGHOUSE:
2 U.S. Nuclear Reactors Construction Halted

But while the article DID include data on EROIs for **oil**,

nowhere in this article,

nor in any of its four cited sources,

did I find a single bit of bit of data about the EROI of nuclear!

SRSROCCO 2017 - Falling EROI kills Westinghouse - Investment Watch

The EROI literature is more sober

But, in the end, it too offers a large dose of controversy!

Based on their own earlier work, and a paper by Lenzen, Murphy & Hall cite:

Nuclear EROI = 5 - 15

Inman, citing both Murphy & Hall, as well as the same Lenzen paper, gives

Nuclear EROI = 5

It thus makes sense to take a much closer look at that Lenzen paper:

It is a fairly recent paper, published in 2008

It has a thorough discussion of methodology (and totals 22 pages)

It draws upon a large number of studies (21 in its EROI relevant table)

But it calculates "Energy Intensity" and not EROI

Murphy & Hall, as well as Inman, apparently assume EROI ~ 1 / (Energy Intensity)

Which is also consistent with my understanding of Lenzen's work

Lenzen 2008 – Lifecycle Energy and Emissions of nuclear - J Energy Conversion and Management

Lenzen's table presenting "energy intensities" for various reactors

Results of energy studies of nuclear power systems

Reference	Year of study	Reactor type	Power rating (MW_{el})	Life time (y)	Load factor (%)	Ore grade (‰)	Enrichment technology	% tails	% ^{235}U in fuel	Conversion rate	Energy intensity $1/R_1$ $\left(\frac{kWh_{th}}{kWh_{el}}\right)$	Analysis type	Stages covered (% of life cycle)	Remarks
[31]	1973	HWR	1000	25	60	3.1	Df		2.1		0.22	I/O	M(2)L(2)V(2)**E(69)** F(1)C(16)O(10)	SGHWR [108]
[31]	1974	HTR	1000	25	60	3.1	Df		6.5		0.31	I/O	M(1)L(1)V(1)**E(85)**F(0)C(11)O(0)	TNPG design
[61]	1975	FBR	1000	25	100	–	–	–	18.0	1.0	0.04	I/O	M(0)L(0)V(0)EFOR(11)**C(89)**	Data in [57]
[31]	1975	HWR	1000	25	60	3.1	–		0.72		0.07	I/O	M(6)L(6)V(6)E(0)F(12)**C(52)**O(18)	Pickering CANDU
[31]	1975	AGR	1000	25	60	3.1	–	–	0.72		0.11	I/O	M(10)L(11)V(10)E(0)F(20)**C(49)**O(0)	Oldbury A Magnox
[17]	1975	HWR	1000	30	75	1.76	–	–	0.72		0.12	I/O	M(4)L(4)V(0)E(0)F(29)**CO(60)**R(3)SW(0)T(1)	CANDU
[17]	1975	PWR	1000	30	75	1.76	Df	0.3	3.2		0.17	I/O	M(2)L(3)V(5)**E(63)**F(5)CO(21)R(0)SW(0)T(0)	Pu rec.
[17]	1975	HTR	1000	30	75	1.76	Df	0.3	93.2	0.66	0.18	I/O	M(2)L(2)V(4)**E(70)**F(2)CO(20)R(0)SW(0)T(0)	^{233}U rec.
[17]	1975	BWR	1000	30	75	1.76	Df	0.3	2.73		0.20	I/O	M(3)L(3)V(6)**E(66)**F(4)CO(17)R(0)SW(0)T(0)	No rec.
[31]	1975	PWR	1000	25	60	3.1	Df		2.7		0.20	I/O	M(2)L(2)V(2)**E(79)**F(1)C(15)O(0)	Shearon Harris
[17]	1975	PWR	1000	30	75	1.76	Df	0.3	3.2		0.22	I/O	M(3)L(3)V(6)**E(68)**F(3)CO(16)R(0)SW(0)T(0)	No rec.
[31]	1975	PWR	1000	25	60	3.1	Df		2.6		0.22	I/O	M(2)L(2)V(2)**E(81)**F(1)C(14)O(0)	Maine Yankee
[17]	1975	PWR	1000	30	75	1.76	Df	0.2	3.2		0.25	I/O	M(2)L(2)V(4)**E(74)**F(3)CO(14)R(0)SW(0)T(0)	No rec.
[31]	1975	PWR	1000	25	60	3.1	Df		3.35		0.26	I/O	M(1)L(2)V(1)**E(83)**F(0)C(12)O(0)	Jos M. Farley
[31]	1975	AGR	1000	25	60	3.1	Df		2.45		0.27	I/O	M(2)L(2)V(2)**E(80)**F(1)C(15)O(0)	Hunterston B
[17]	1975	HTR	1000	30	75	0.06	Df	0.3	93.2	0.66	0.29	I/O	M(10)**L(33)**V(2)E(42)F(1)CO(12)R(0)SW(0)T(0)	^{233}U rec.
[17]	1975	PWR	1000	30	75	0.06	Df	0.3	3.2		0.32	I/O	M(12)**L(39)**V(3)E(33)F(3)CO(11)R(0)SW(0)T(0)	Pu rec.
[31]	1975	PWR	1000	25	60	3.1	Df		3.3		0.37	I/O	M(1)L(2)V(2)**E(87)**F(0)C(8)O(0)	Haddam Neck
[17]	1975	PWR	1000	30	75	0.06	Df	0.3	3.2		0.46	I/O	M(13)**L(43)**V(3)E(32)F(2)CO(8)R(0)SW(0)T(0)	No rec.
[60]	1976	HWR	1000	25	60	3.0	Df	0.25	2.1		0.24	I/O	M(2)L(2)V(2)**E(69)**F(1)C(21)O(3)	CANDU
[60]	1976	HWR	1000	25	60	0.07	Df	0.25	2.1		0.28	I/O	M(9)**L(39)**V(1)E(29)F(0)C(18)O(3)	CANDU
[34]	1978	FBR	1300	25	79.9	–	–	–			0.019	I/O	FO(19)**C(81)**	
[34]	1978	LWR	1300	25	79.9	2	Ce				0.04	I/O	**MLVEFO(71)**C(29)	
[34]	1978	HTR	1300	25	79.9	2	Ce				0.04	I/O	**MLVEFO(66)**C(34)	
[34]	1978	HTR	1300	25	79.9	0.2	Ce				0.13	I/O	**MLVEFO(89)**C(11)	
[34]	1978	LWR	1300	25	79.9	0.2	Ce				0.16	I/O	**MLVEFO(92)**C(8)	
[34]	1978	LWR	1300	25	79.9	2	Df				0.18	I/O	**MLVEFO(93)**C(7)	
[34]	1978	HTR	1300	25	79.9	2	Df				0.21	I/O	**MLVEFO(93)**C(7)	
[34]	1978	LWR	1300	25	79.9	0.2	Df				0.29	I/O	**MLVEFO(96)**C(4)	
[34]	1978	HTR	1300	25	79.9	0.2	Df				0.30	I/O	**MLVEFO(95)**C(5)	
[48]	1983	PWR	1000	25	75	≈3	Ce		3.0	0.55	0.11	AEI	MLV(12)EF(7)**C(68)**O(11)S(1)W(1)	Biblis A[c]
[62]	1988		1000	30	50						0.85[d]	AEI	MLVEF(12)**C(67)**OT(18)DSW(3)	
[56]	1992	PWR	1000	30	75		Df				0.19	I/O	M(3)L(3)V(7)**E(66)**F(3)C(8)O(9)R(0)S(0)T(0)	
[109]	1996	FBR	1000	30	75	–	–	–			0.009	I/O		
[110]	1999	BWR	1000	30	75		Ce			30[b]	0.036	I/O	ML(1)V(10)E(22)F(2)**O(33)**R(22)D(0)SW(10)	Pu recycle
[110]	1999	BWR	1000	30	75		Df			30[b]	0.10	I/O	ML(1)V(4)**E(81)**F(1)O(11)D(0)SW(2)	
[83]	2000	PWR	1000	40	86.8						0.006	PA	COD(100)	Doel 3/4
[83]	2000	PWR	1000	40	86.8						0.018	I/O	COD(100)	Doel 3/4
[53]	2000	PWR	1000	40	75		Ce		3.0		0.06	I/O	M(5)**LVEF(63)**C(10)O(12)D(1)SW(9)T(0)	
[42]	2001	PWR	1000	30	80	0.2	Df		3.2		0.14	PA	**MLE(86)**V(6)C(4)S(4)	U from Ranger mine, US grid
[46]	2004	PWR	1000	40	81.4	2.0	Df	0.26	3.8	42.8[b]	0.03	PA		MOX fuel
[46]	2004	BWR	1000	40	81.4	2.0	76% Ce	0.26	4.0	48[b]	0.045	PA		MOX fuel
[30]	2005	PWR	1000	24	82	1.5	70% Ce	0.2	4.2	46[b]	0.66[a]	AEI	ML(3)V(2)E(13)F(1)**C(24)**O(15)**D(24)**S(9)W(11)	
[30]	2005	PWR	1000	24	82	0.1	70% Ce	0.2	4.2	46[b]	1.63[a]	AEI	ML(22)V(1)E(5)F(0)C(10)O(6)D(10)S(4)**W(44)**	
[47]	1975	BWR	1000	30	80		Df		2.6	27[b]	0.063	I/O	M(0)L(2)**E(62)**F(0)C(36)R(0)	
[47]	1975	PWR	1000	30	80		Df		3.0	33[b]	0.064	I/O	M(0)L(2)**E(64)**F(0)C(33)R(0)	
[111]	2000	PWR	1000	30	75		Df				0.064		M(0)L(6)V(3)**E(71)**F(1)C(8)O(12) T(0)	
[102]	1977	PWR	1000	30	75	1.5	Df	0.3			0.2	I/O		U + Pu recycling
[9]	1976	LWR	1000	40	80	2.34	Df	0.25	2.3	45[b]	0.171	I/O	ML(1)V(5)**E(72)**F(3)CO(14)D(3)ST(1)	Ore from Ranger
[9]	1976	LWR	1000	40	80	2.34	Ce	0.25	2.3	45[b]	0.052	I/O	ML(3)V(18)E(6)F(11)**CO(47)**D(12)ST(3)	Ore from Ranger
[9]	1976	LWR	1000	40	80	0.1	Df	0.25	2.3	45[b]	0.206	I/O	ML(18)V(4)**E(60)**F(3)CO(12)D(3)ST(1)	
[9]	1976	LWR	1000	40	80	0.1	Ce	0.25	2.3	45[b]	0.087	I/O	ML(42)V(11)E(4)F(7)**CO(28)**D(7)ST(2)	

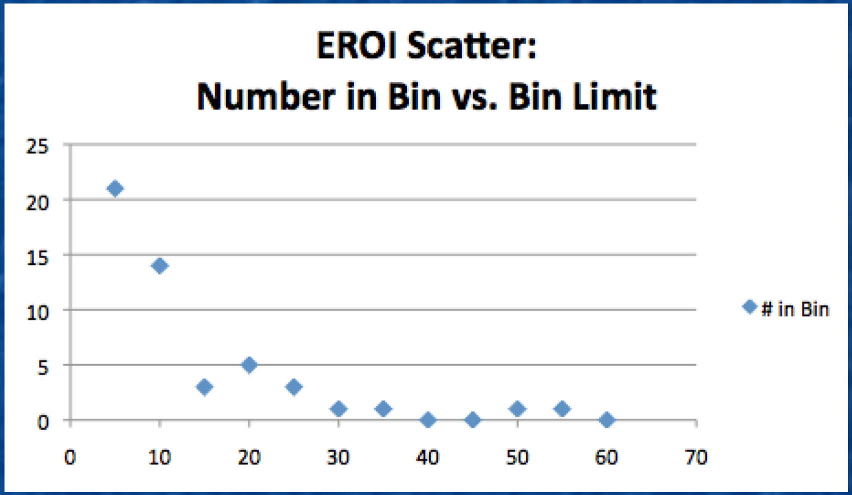
I ended up entering these data into an Excel spreadsheet

Which I provide on this note set's **Resources Webpage**

I did this for reasons I'll only fully explain a few slides further on

Taking the reciprocal of the "energy intensity" values that I highlighted in yellow

I generated this EROI scatter plot:



And I got an EROI average of **15.3**

But **many** of that table's EROIs are instead in the 20's, 30's and even 50's

That is a VERY LARGE data scatter!

Especially for what should have been a pretty unambiguous energy calculation!

This prompted me to go looking for other data sources

Particularly sources taking into account the many differences between reactors

that I have learned about in my studies of nuclear energy

Differences between, for example, heavy and light water reactors:

One requiring energy-intensive heavy water enrichment

The other requiring energy-intensive uranium enrichment

Or differences between common light water reactors such at BWRs and PWRs

Which employ significantly different energy transfer schemes

But perhaps most importantly, **given the newness of nuclear energy**:

I wanted data relevant to **today's commercial reactors**

as opposed to more **primitive research reactors** built in the 50's & 60's

But I found few studies of that sophistication

And when I did find them, they often came from less than disinterested sources

Such as the World Nuclear Association (WNA)

The WNA has a lengthy 2017 webpage providing comparative EROI data

For centrifuge-enriched uranium fueled (= light water) reactors it gives this:

		Source:	EROI:
Nuclear (centrifuge enrichment)	PWR/BWR	Kivisto 2000	59
	PWR	Weissbach 2013	75
	PWR	Inst. Policy Science 1977*	46
	BWR	Inst. Policy Science 1977*	43
	BWR	Uchiyama et al 1991*	47

But these sources are NOT from the nuclear industry, they're 3rd party studies

One of which I immediately recognized:

WNA 2017 - Nuclear Energy Return on Investment

Weissbach's 2013 comparative EROI study

Which is cited frequently and favorably throughout the EROI literature

Which had already led **me** to cite its results throughout this note set!

But Weisbach comes up with a radically higher **Nuclear EROI = 75**

He acknowledges that others calculate Nuclear EROI "a factor of 20 lower"

Including EROI research pioneers such as Hall

But he forcefully critiques those studies as:

"extremely unphysical" and/or **"unsuitable for comparison"**

He also notes that some still assume a < 40 year nuclear plant lifetime

Despite most nuclear plant operating licenses now being extended to 60 years

This, alone, could boost nuclear plant EROI by up to 50%

Weissbach 2013 - Energy intensities EROIs and energy payback times of electricity generating power plants - Energy

But how can Lenzen's & Weissbach's conclusions differ so radically?

THIS is what led me to enter Lenzen's earlier data into a spreadsheet

I wondered if the discrepancy lay in his inadequate data **analysis**

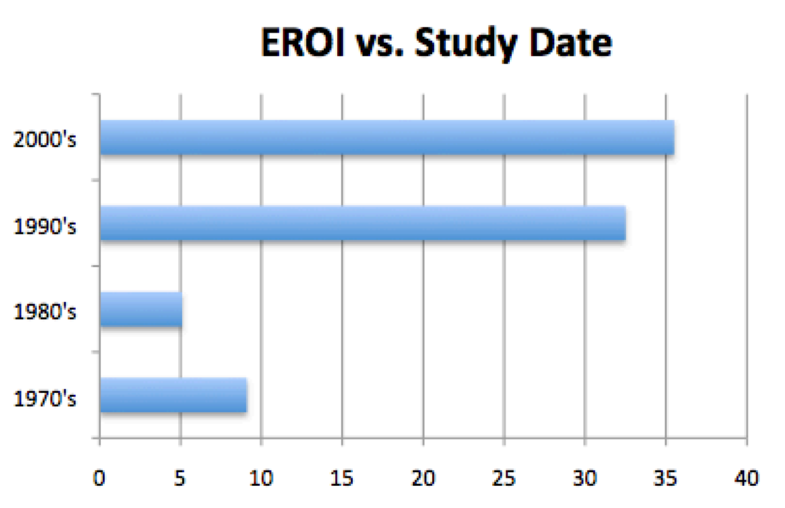
Specifically: Not filtering for data on more modern commercial reactors

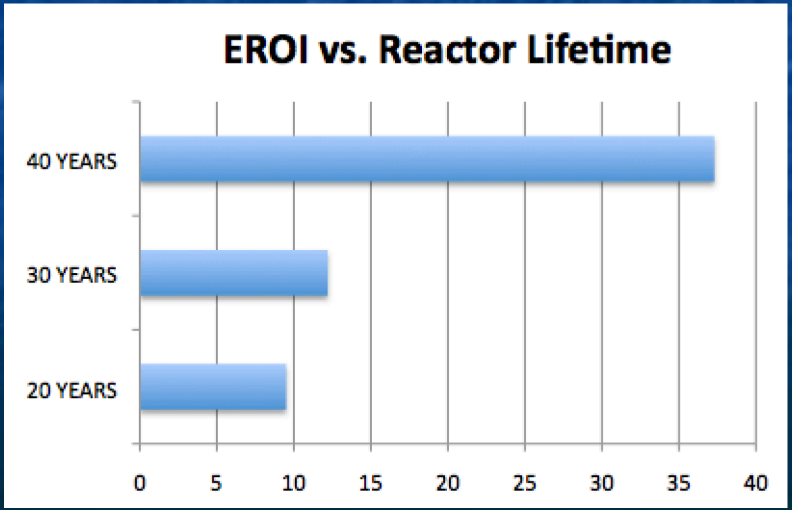
I could have dug through all 21 of his sources, identifying the reactors they studied

But modern commercial reactors should dominate **more recent studies**

And they should be identifiable based on their **longer operational lifetimes**

Resorting Lenzen's table 13a data according to those criteria, I then found:





Leading to my very different conclusions about Nuclear EROI:

A simple average of Lenzen's data gave a **Nuclear EROI = 15.6**

Leading to Murphy & Hall's Nuclear **EROI = 5-15** and Inman's Nuclear **EROI = 5**

Weisbach calculated a much larger value of **Nuclear EROI = 75**

But motivated by my **technical knowledge about nuclear reactor evolution**

I generated two resorts of Lenzen data highlighting modern commercial reactors

While these did not quite close the gap with Weissbach, they came very close:

Showing that even Lenzen's data supports a **Modern Nuclear EROI ~ 35-40**

NOTE: For both wind & nuclear I've now arrived at EROIs far above accepted values

WHY? Because researchers failed to recognize the evolution of those technologies

Leading to EROIs grossly misrepresenting their current state of development

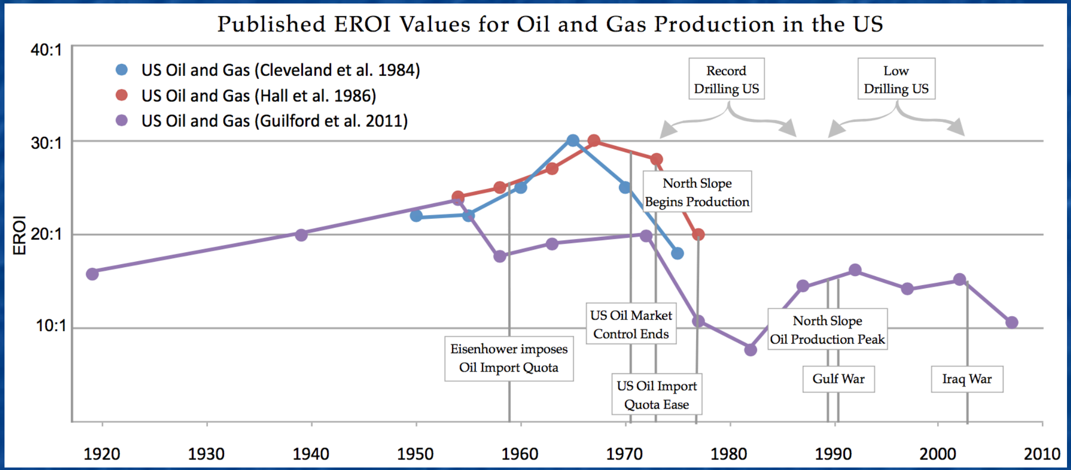
Finally moving on to:

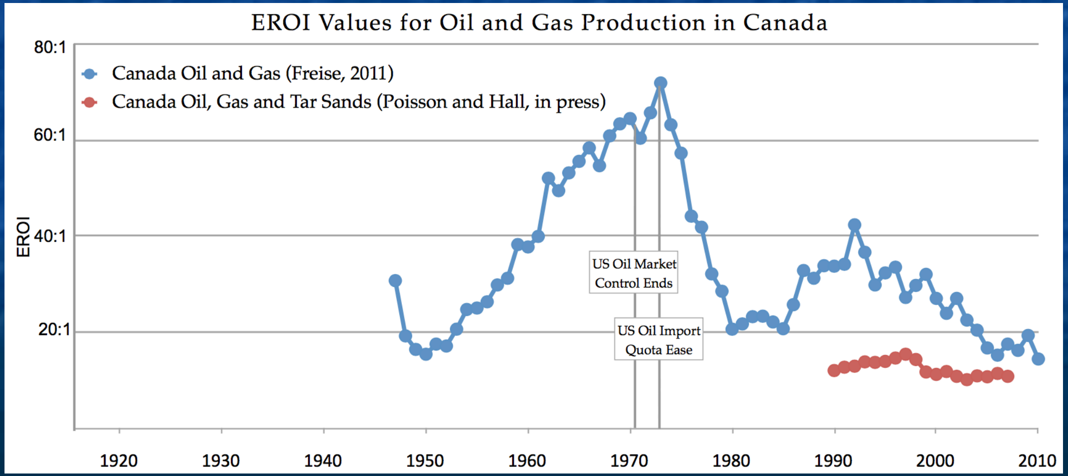
EROIs for Fuel Heat Generation

*Here, ironically, research now **focuses** on time evolution*

Because that evolution has become so very pronounced

As seen in these figures from a UK government review led by Lambert:

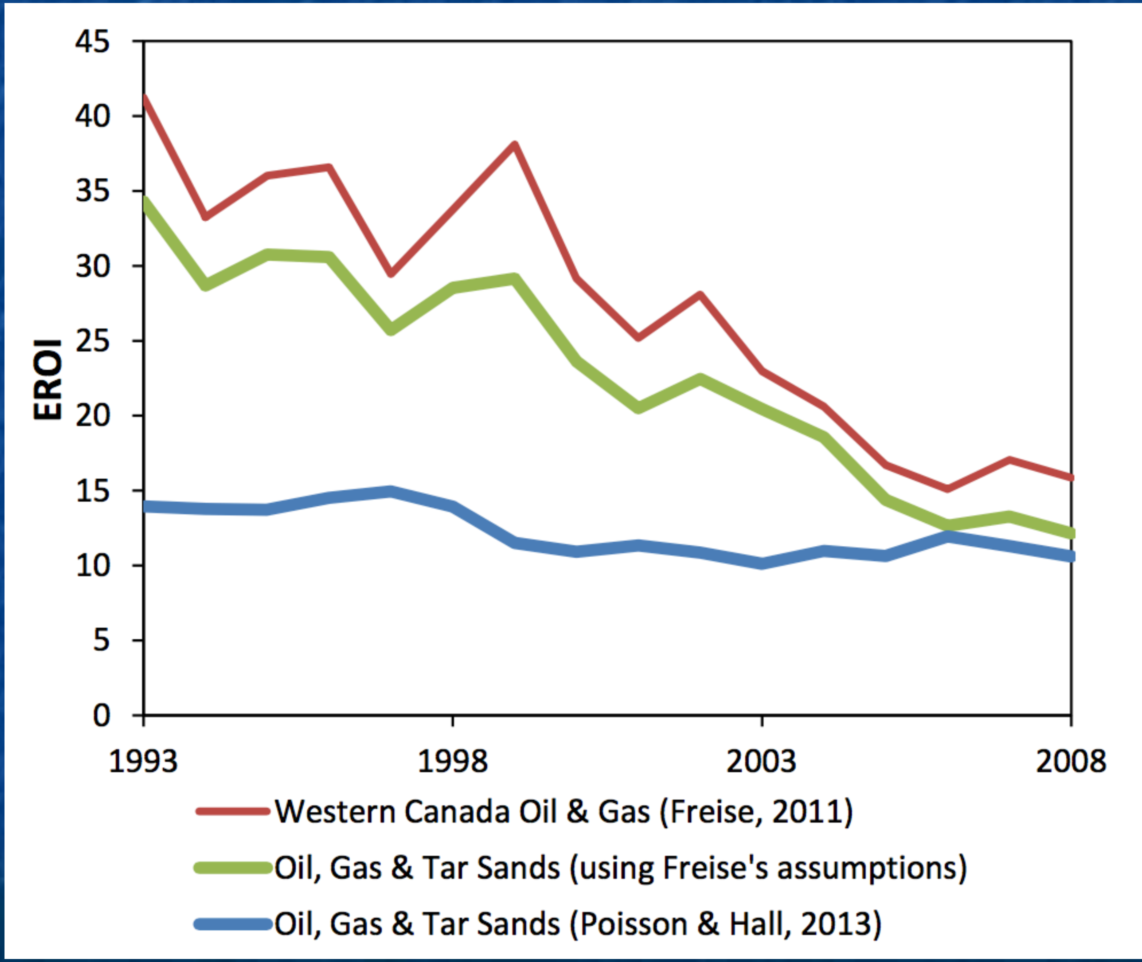




Lambert 2013 - EROI of Global Energy Resources - Status Trends Social Implications - Lambert - UK DID

*That evolution, in recent years, has been steadily **downward:***

As seen in this data summary from Poisson et al. in 2013:



Poisson 2013 - Time Series EROI for Canadian Oil and Gas

These curves echo the "Hubbert's Peak" phenomenon of:

A fuel's production following a bell-shaped curve over time

Because initial demand drives discovery of greater and greater reserves

(likely also driving development of LESS energy intensive extraction techniques)

Leading to increased production

Leading to increased dependence on that fuel

Driving up that fuel's price until:

Reserves of easily accessible fuel are depleted

Forcing a switch to less accessible deposits

(likely requiring much MORE energy intensive extraction techniques)

Which then drives the price of that fuel so high

That customers (and suppliers) seek out alternative fuels

Driving production of the initial fuel sharply back down

But, once again, one must be wary of lumping too much data together:

In the preceding section such lumping obscured technological evolution

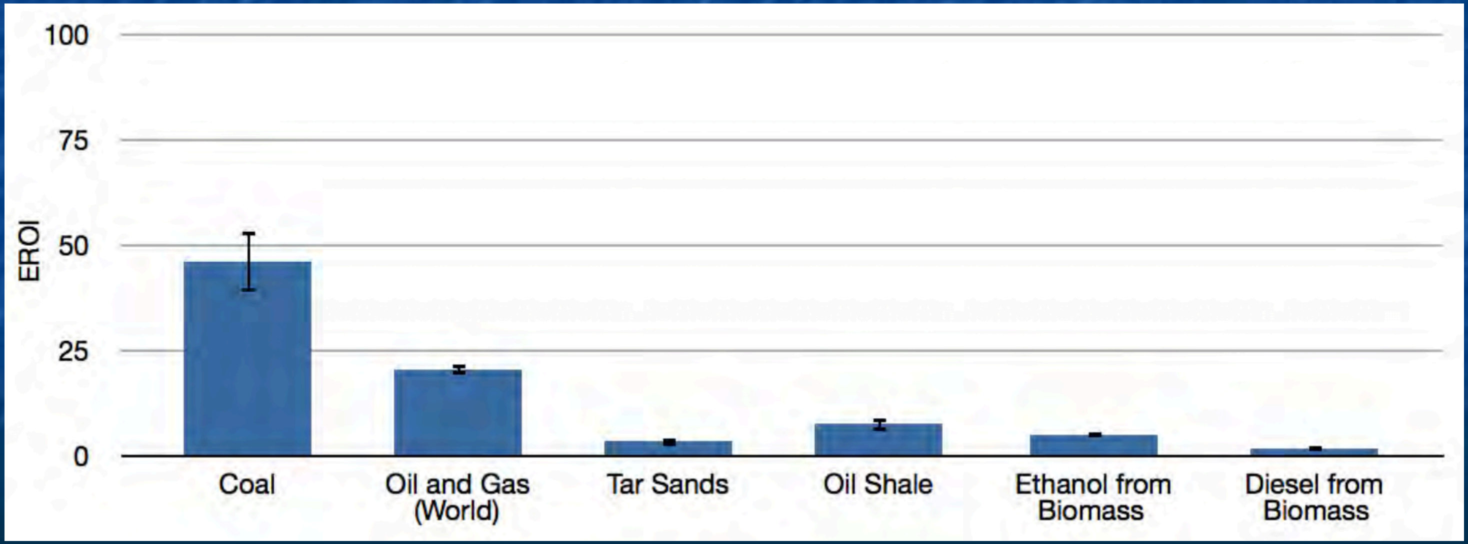
Leading EROI studies to seriously undervalue current wind & nuclear technology

Likely undercutting the quality of sustainable energy decision making!

Here, instead, a research penchant for lumping all fossil fuels together

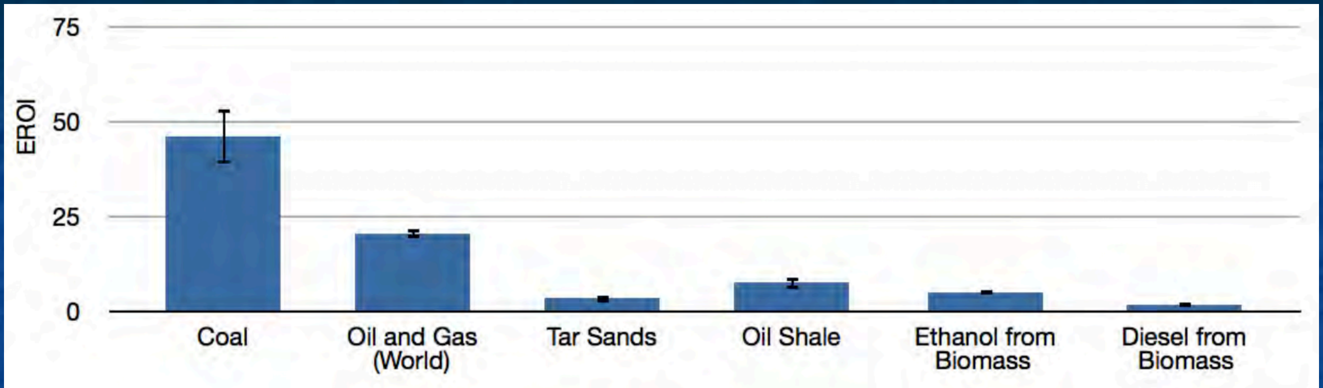
can obscure the very pronounced differences which still exist between them

Which, admittedly, IS recognized in this figure from Lambert:



Lambert 2013 - EROI of Global Energy Resources - Status Trends Social Implications - Lambert - UK DID

Looking at those differences more closely: COAL



COAL's EROI has fallen sharply:

Where Murphy & Hall's 2010 summary of historic data gave **Coal EROI = 80**

In 2013 Lambert identified the then current value as **Coal EROI = 45**

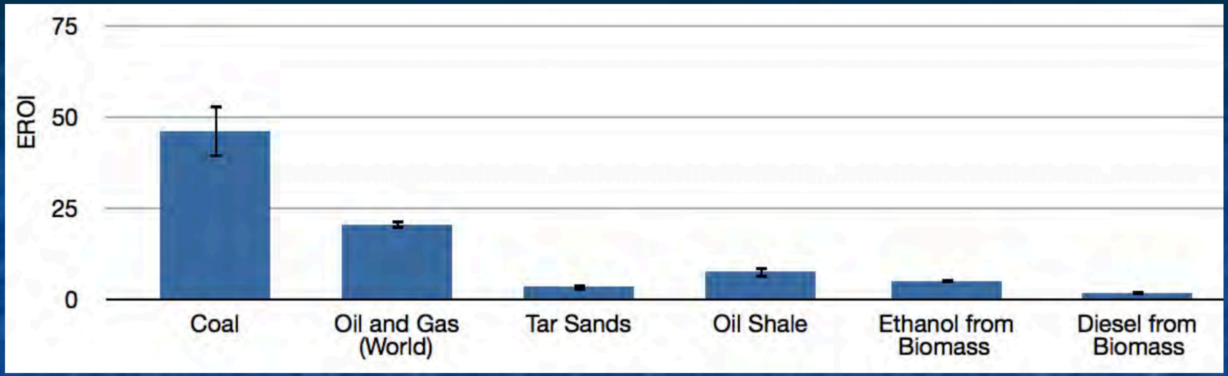
But both implicitly assume that you do nothing to offset coal's pollution

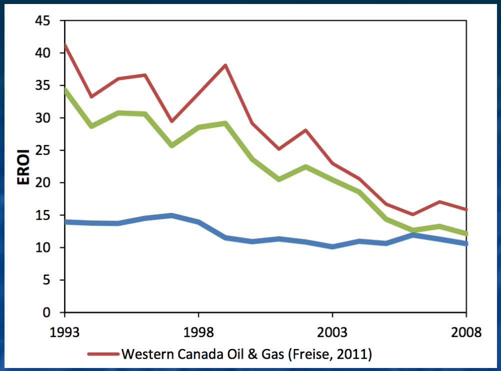
If pollution is instead filtered out by adding pollution control technology

the example of coal-powered electrical plants suggests

EROIs may decrease by a factor of ~ 10X => **Coal EROI ~ 5**

OIL & GAS:





Lambert (lumping them together) gives **O & G EROI ~ 20**

Versus Murphy & Hall's separate **OIL EROI = 12-35** and **NG EROI = 10**

Decreasing supply + increasingly difficult extraction now drive both downward

But as a heat-producing fuel, oil and gas retain two crucial advantages:

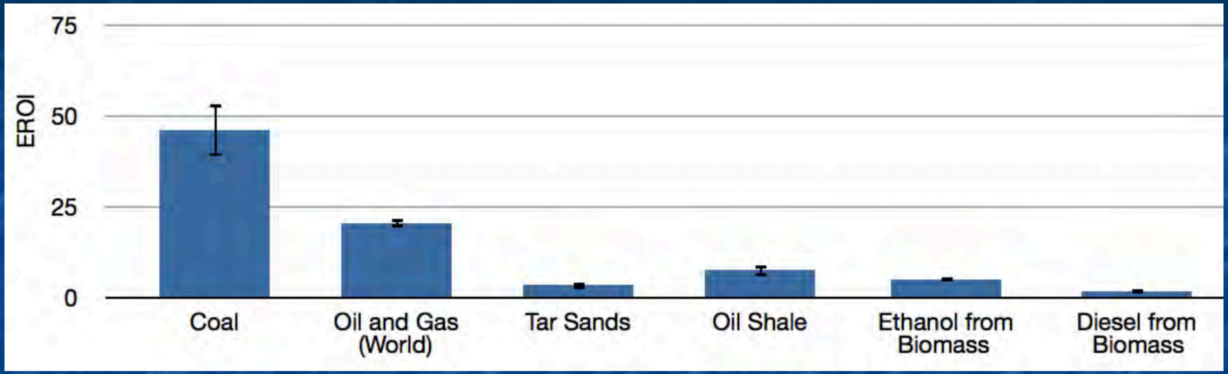
1) Both can burn comparatively cleanly (at least if one ignores carbon footprint)

2) Both offer an **EXTRAORDINARY** amount of heat energy per mass

Making them today's **1st choice** for powering ground and sea transportation

And today's **only viable choice** for powering air transportation

And then there are four apparent losers:
Tar Sands, Oil Shale, Ethanol & Diesel from Biomass



However, the petroleum industry is putting intense effort into tar sands & oil shale,

leading to intense concern about not only their environmental impacts,

but also about the impact of new pipelines proposed for their transportation

And while ethanol and diesel from biomass are traditional "green energy" darlings,

not only are their EROI's at the bottom of the heap but they even

flirt with EROI = 1 which would transform them into **net energy sinks**

Why are these fuel EROIs so terribly low?

Tar Sands and Oil Shale:

Gases and liquids flow easily out of wells, sometimes even without pumping!

But Tar Sand & Oil Shale are tar **embedded** in sand or finely grained rock:

Tar Sand:

Oil Shale:

Extracting these requires either:

1) Mining them out of the ground and then

2) Applying so much **HEAT** that the tar melts into flowable oil

OR: 1) **HEATING** them while still in the ground (via steam injection) and then

2) Pumping out the liquefied tar

https://www.2b1stconsulting.com/oil-sands/

http://ostseis.anl.gov/guide/oilshale/index.cfm

But both mining & pumping require energy,

and heating requires MAJOR energy!

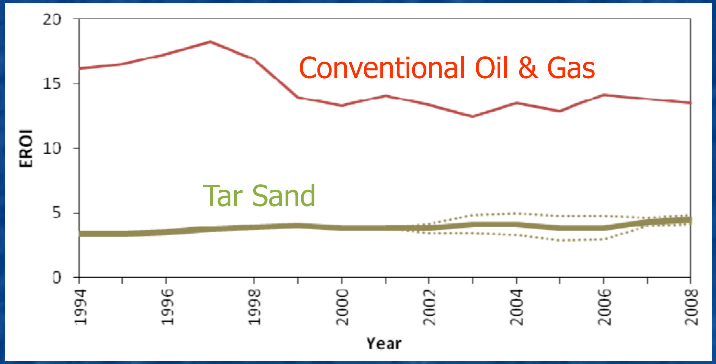
In fact, that heat is often obtained by burning up

a good fraction of the fuel just extracted!

Extraction of fuel from both Tar Sands and Oil Shales is relatively new

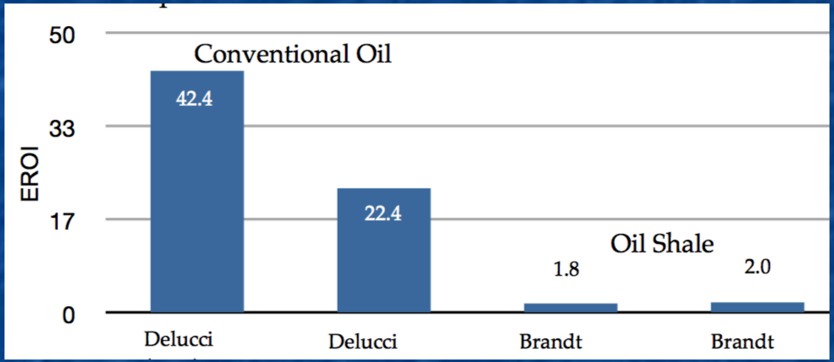
One article even described existing technology as more of a field experiment

But Poisson 2013 presented this:



Tar Sand EROI = 3-5

And Lambert 2013 offered this:



Oil Shale EROI = 1.8-2

NOTE (!): Lambert's summary figure (shown 2 slides ago) instead shows Oil Shale EROI ~ 7

Poisson 2013 - Time Series EROI for Canadian Oil and Gas

Lambert 2013 - EROI of Global Energy Resources - Status Trends Social Implications - Lambert - UK DID

*Biofuel EROIs are **also** driven down by excessive energy inputs:*

From my Biomass & Biofuels (pptx / pdf / key), ethanol production requires **energy** to:

- Synthesize the exceptionally large quantities of fertilizer required by corn
- Break down the 'ligno cellusosic matrix" of that corn to expose its cellulose
- Rid the resulting "mash" of bacteria that could interfere with yeast growth
- Provide the sustained warmth that yeast requires to ferment sugars into alcohol
- Provide the sustained heat that distillation requires to separate out that alcohol

The exact steps may change if sugar cane is the feedstock

or if biodiesel is to be the output

But multiple biological and/or chemical synthesis steps

combined with final fuel separation steps

inevitably => exceptionally large energy inputs

Figure: http://www.apptrav.com/howto.html

And there is also the issue of ***not very well hidden research agendas***

EROI was defined as: **Lifetime Energy Output / Lifetime Energy Input**

Thus, if harvesting sugar for ethanol involves burning off its fields,

that heat is considered an energy input because it could have been used

instead to homes, to create the steam in an electricity plant . . .

But many biofuel studies choose to redefine EROI as instead:

Lifetime Energy Output / Lifetime <u>Fossil Fuel</u> Input

Some even consider only inputs of single specific fuel

Why the sudden redefinitions? Because these studies are primarily focused on

eliminating the atmospheric carbon footprint of today's fossil fuels

And from such a climate-change-driven perspective,

YES, a fuel requiring less fossil fuel to create is more desirable!

*But EROI's were meant to **clarify** our energy decisions*

Whereas mobile EROI definitions seem to only cloud those decisions. For example:

Airlines may soon be compelled to adopt supposedly carbon-neutral biofuels [1]

But if we force such a change, it will not be because it makes **energy sense**

It will be because it makes unavoidable **climate sense**

Why? Because jet travel can account for 1/3 of your personal carbon footprint

Its elimination may thus be so important that we switch to carbon-neutral fuels

even if those aircraft biofuels end up being net energy sinks!

Or to instead call upon Murphy & Hall's words from their seminal EROI publication: [2]

"In the case of corn ethanol, at least three different methods of net energy analysis had been employed in the literature, resulting in three different estimates of EROI that were **mutually incommensurable**"

1) For further discussion of biofuels in aviation, see my Biomass & Biofuels (pptx / pdf / key) note set

2) Murphy 2010 - Year in Review: EROI or Energy Return on (Energy) Invested

Specific sources of dispute?

- Missing energy inputs (e.g. for fertilizers or for farm machinery & infrastructure)

- Inflated claims about possible secondary use of energy

As in the possible use of waste heat for local heating of buildings

or for steam production in adjacent electrical power stations

- Inflated claims of byproduct ("co-product") energy value (output)

As in claims that used corn mash could largely replace corn livestock feed

despite fermentation having depleted it of much of its nutritional value

- Counter claims that co-product energies were omitted in specific papers

Despite clear evidence I found of their being included in those exact papers

(They might have been undervalued, but they weren't omitted!)

For more specifics, see the dozen plus biofuel papers I cite on the Resources Webpage

Hall and Lambert looked back on all of this in a joint 2014 review:

In that review they considered biofuel EROI research

From no less than 31 different studies

Considering feedstocks of wood, corn, sugar cane, molasses . . .

Which they rolled into a composite statement that **Biofuel EROI ~ 5**

But, as I've discovered, lumping EROI data together can be a lousy idea

Which almost compelled me to dig up each of those 31 studies

Separating EROI's for each feedstock, sorting data by date of study, etc.

Which I might have done had I not come to share their conclusion about biofuels:

"We believe that outside certain conditions in the tropics most ethanol EROI values are at or below the 3:1 minimum extended EROI value required for a fuel to be minimally useful to society"

(John: But add to this their possible use in mitigating aviation's carbon footprint!)

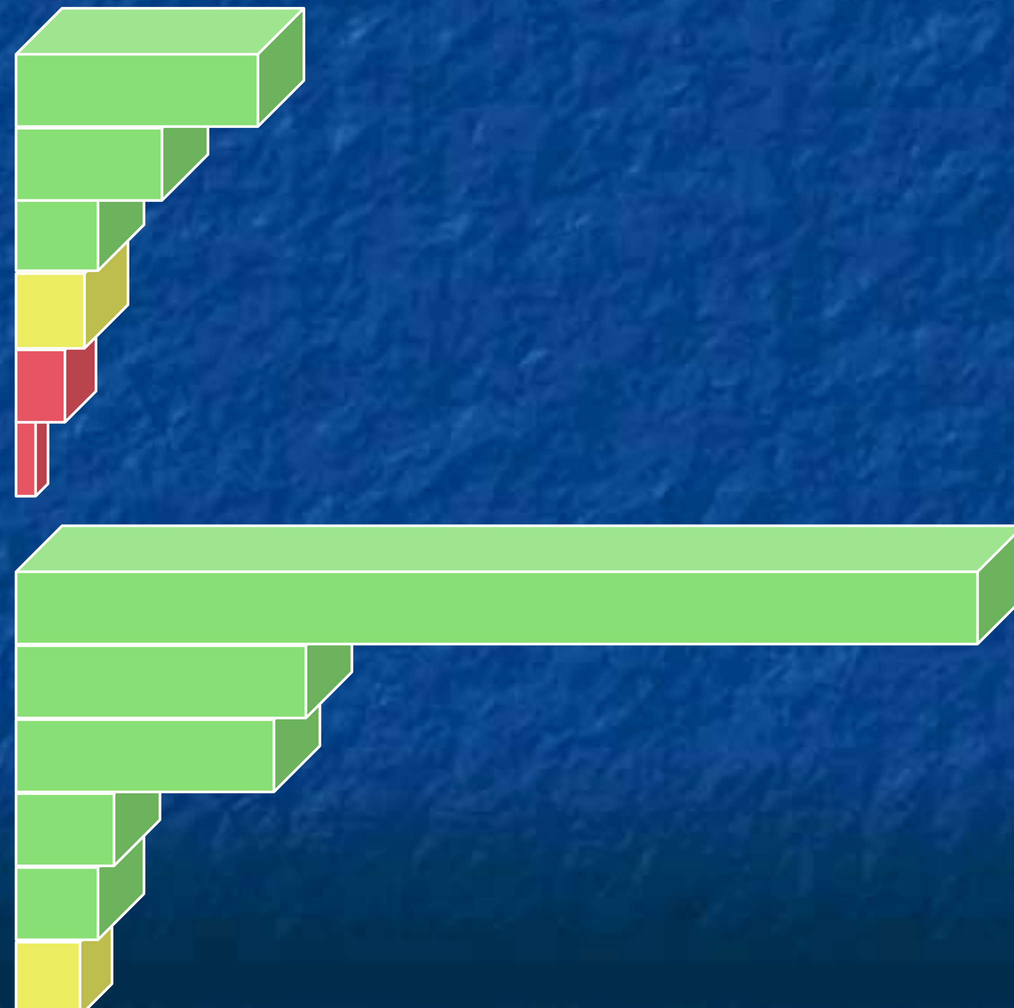
Hall, Lambert & Balogh 2014 - EROI of Different Fuels and the Implications for Society

*Thus jumping forward to **my** conclusions about EROI*

My earlier rendition of the Murphy & Hall / Scientific American 2013 data

Colors reflect articles' conclusion that economic viability requires EROI of ~ **3-5**

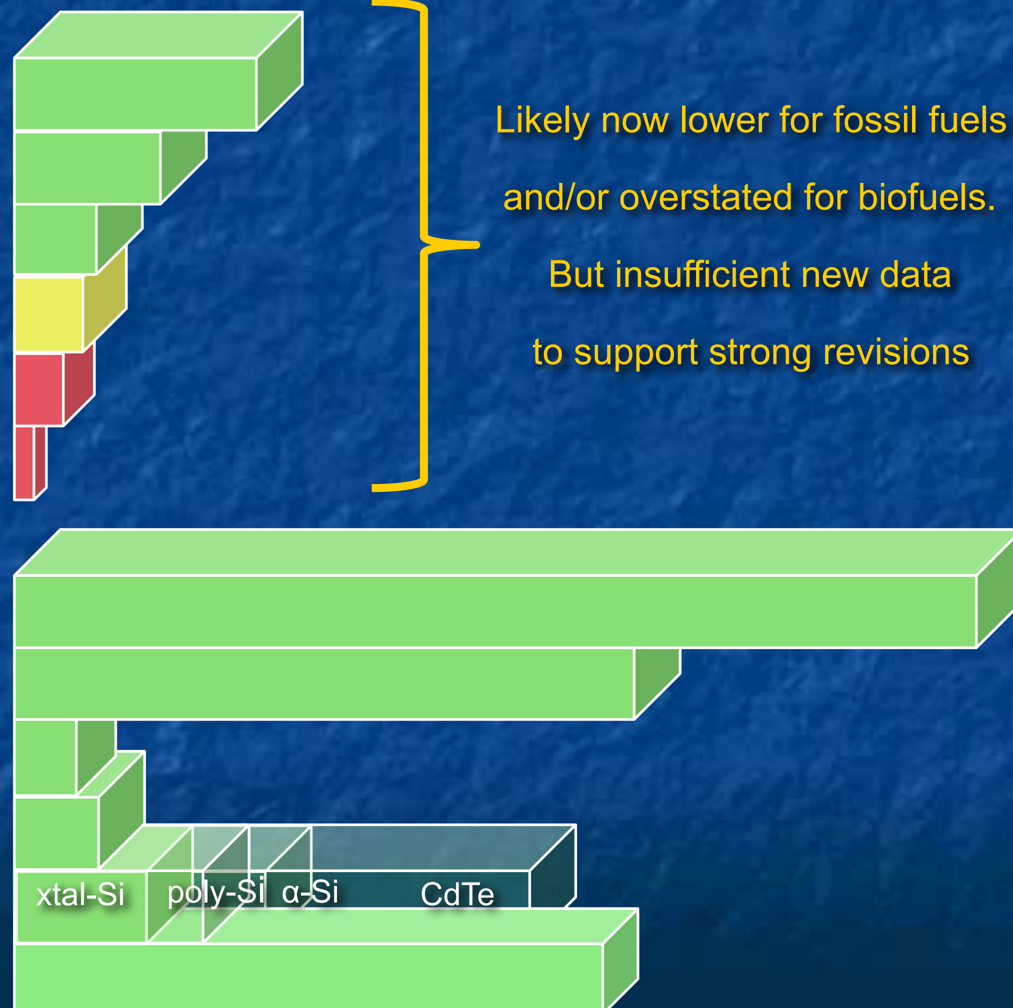
Technology	EROI
Heat from:	
Conventional oil	16
Ethanol from sugarcane	9
Biodiesel from soy	5.5
Tar Sands	5
Heavy oil from California	4
Ethanol from corn	1.4
Electricity from:	
Hydroelectric Dams	40+
Wind	20
Coal	18
Natural Gas	7
Solar PV	6
Nuclear	5



Versus my updated / expanded analysis of at least power plant EROI data:

Colors reflect articles' conclusion that economic viability requires EROI of ~ **3-5**

Technology	EROI
Heat from:	
Conventional oil	16
Ethanol from sugarcane	9
Biodiesel from soy	5.5
Tar Sands	5
Heavy oil from California	4
Ethanol from corn	1.4
Electricity from:	
Hydroelectric Dams	40+
Wind	~ 40
Coal (CC)	2.5-5
Natural Gas (CCGT)	3.5-5
Solar PV	9, 12, 15, 35
Nuclear	35-40



Likely now lower for fossil fuels and/or overstated for biofuels. But insufficient new data to support strong revisions

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