The SOLAR TRANSITION:
shifting to a fully Renewable Energy System

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Central Questions Facing Humanity in 21st Century

(1) What are we going to use for energy?

Caveats:

(A) planet doesn't bake, millions don't die
(B) everyone gets enough
(C) geopolitical harmony achieved

} **R.E.** (Not F.F.)

Transition needed

Central Questions Facing Humanity in 21st Century

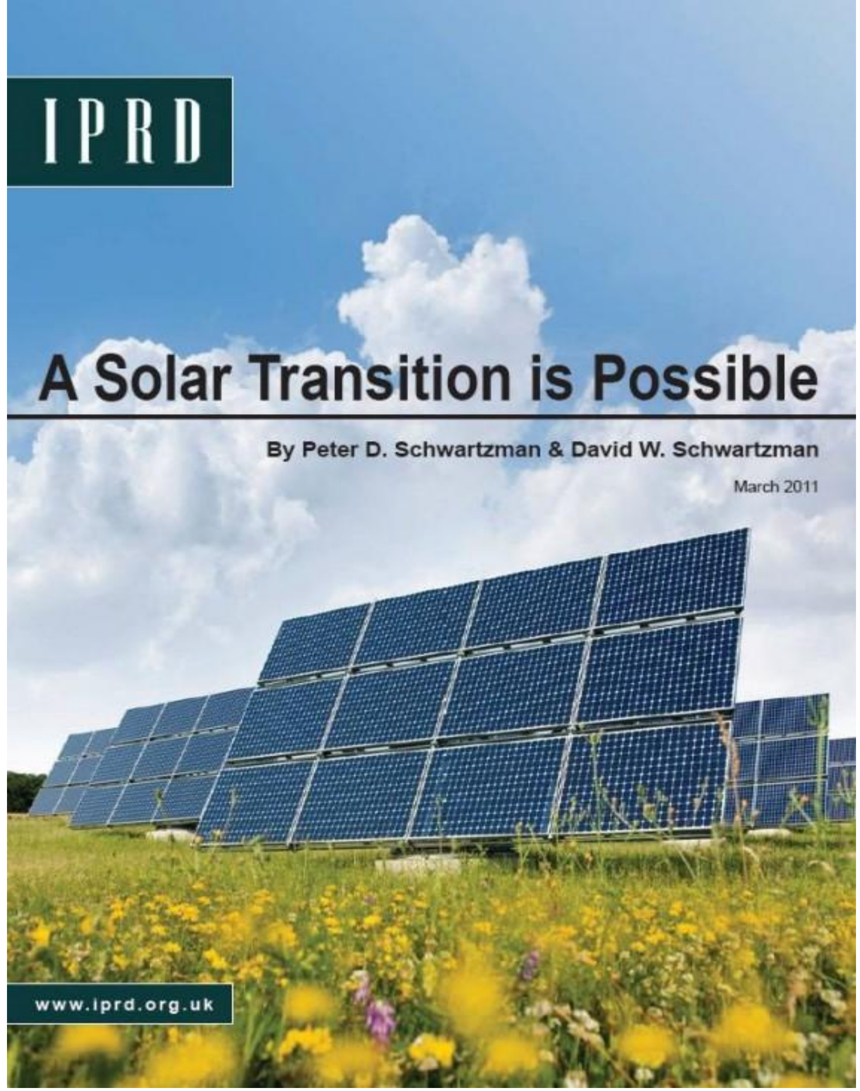
Transition needed

(2) Can we fuel the world with R.E. alone?
NOW & in FUTURE

YES!

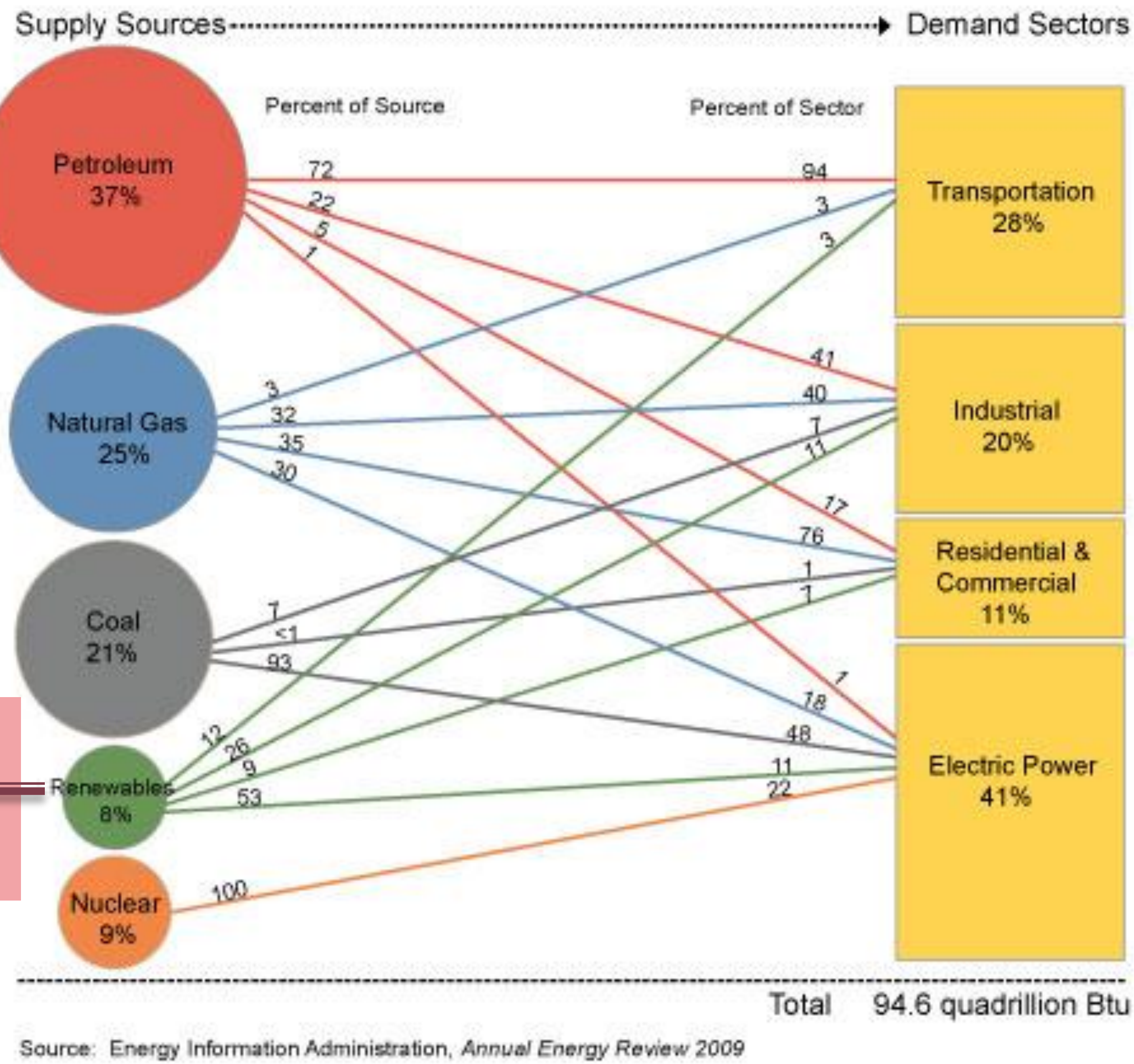
(JACOBSON & DELUCCHI, 2009; SAWIN & MOOMAW, 2009)

So we decided to find out <u>how long</u> & <u>how much F.F.</u> for the transition.



Co-authored & Peer-reviewed
Institute for Policy Research & Development
published March 2011
(posted at iprd.org.uk)

What does our energy picture look like?



<1%:
Wind
Solar (PVC, solar hot water)

What does our energy future look like?

International Energy Outlook 2010

July 2010

U.S. Energy Information Administration
Office of Integrated Analysis and Forecasting
U.S. Department of Energy
Washington, DC 20585

Look at contents of report.

What do you notice?

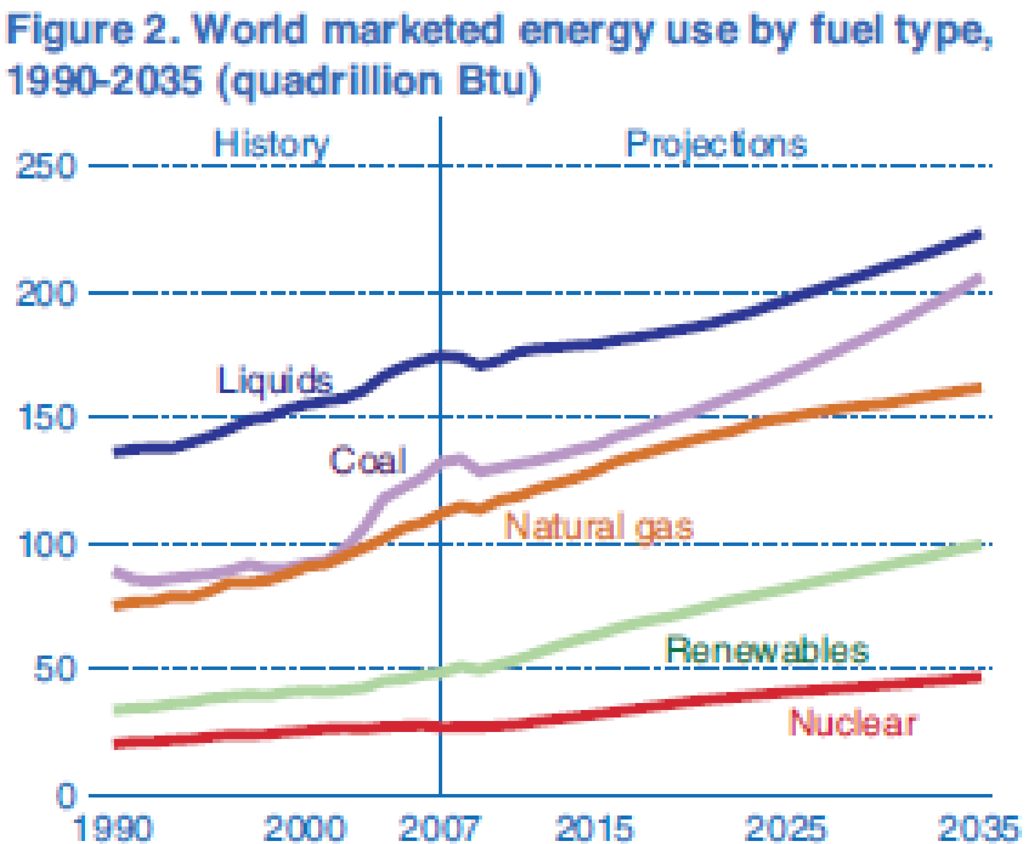
1 Quad?

- 1 Quad = 1 Quadrillion BTUs
  = 1×10^{15} BTUs
  = 8 billion gallons of gasoline (ee)
  = 36 million tonnes of coal (ee)
  = 293 million kWh

ee = energy equivalent

World energy production (annually): **~450 Q**

EIA Projections



Source: U.S. EIA's *International Energy Outlook 2010*

World Energy Consumption (WEC)

In 2007:

Non-Renewables: 446Q (90.1%)

Renewables:

Electricity (wind-IC): 2.8Q

Electricity (solar-IC): 0.2Q

(IC = installed capacity)

In 2035:

Non-Renewables: 557Q (87.1%)

Renewables:

Electricity (wind-IC): 14.5Q

Electricity (solar-IC): 1.9Q

Projections

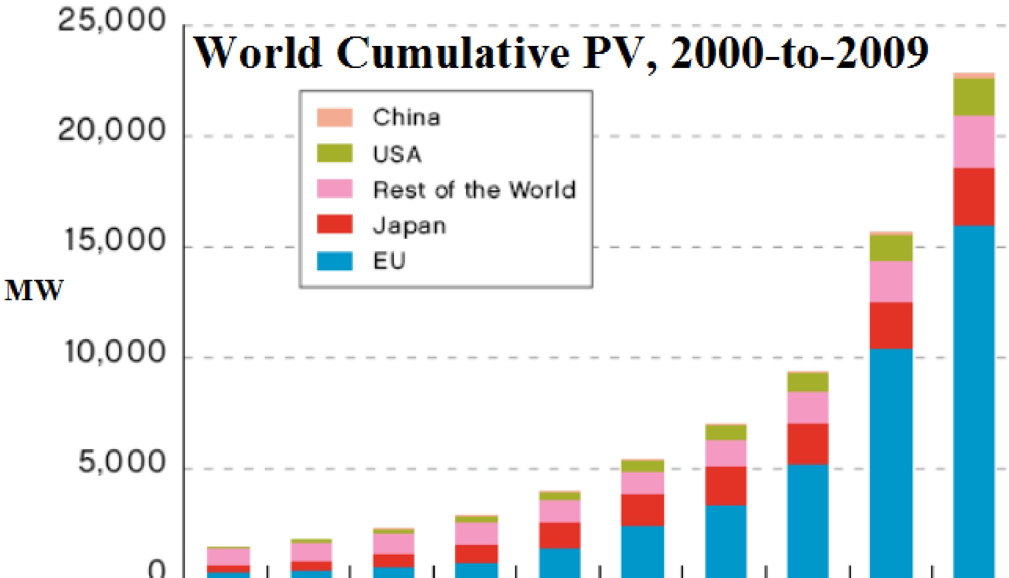
<u>(annual growth rate, 2007-2035)</u>

Non-Renewables: 0.8%

Renewables: 2.6%

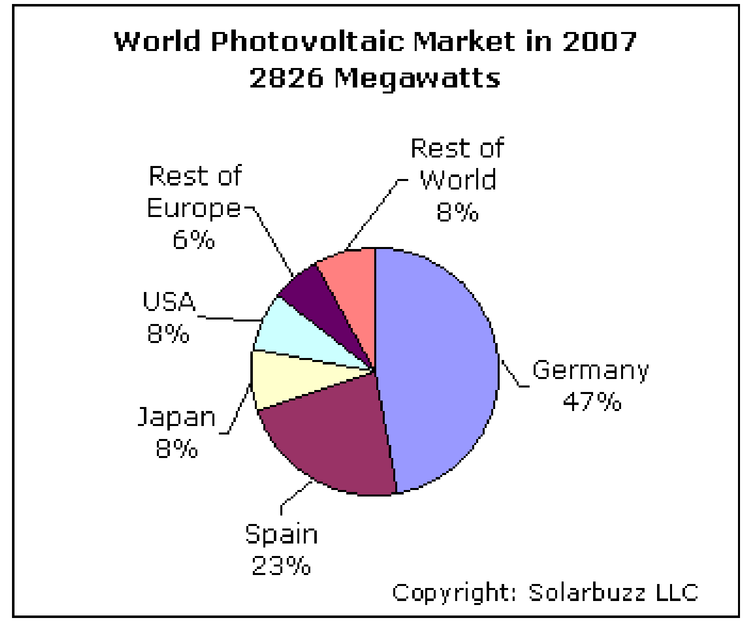
Wind & Solar (installed): 6.3%

Growth in Installed Solar (PV) Capacity



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
China	19	30	45	55	64	68	80	100	145	305
USA	139	168	212	275	365	479	624	831	1,173	1,650
ROW	763	825	913	1,000	1,044	1,051	1,235	1,422	1,870	2,347
Japan	318	452	637	860	1,132	1,422	1,708	1,919	2,149	2,633
EU	189	286	422	633	1,319	2303	3,282	5,088	10,340	15,958

(from EPIA's *Global Market Outlook for Photovoltaics…*)

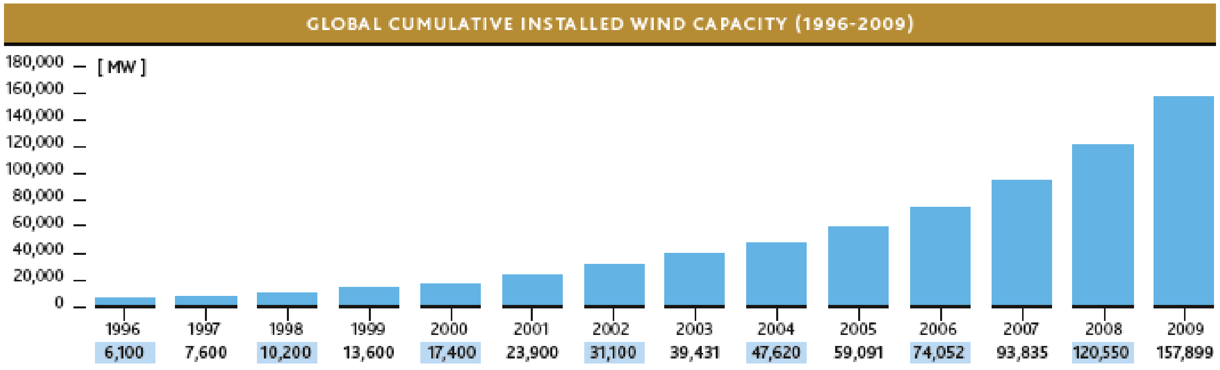


23 GW (~0.7 Q)

36% annual growth for 9 years!

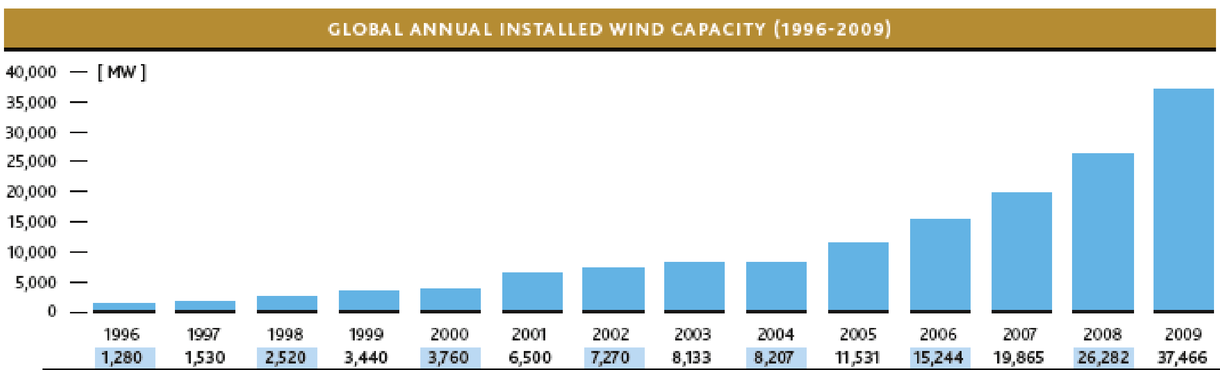
What's been happening?

GROWTH OF INSTALLED WIND POWER CAPACITY



28% annual growth for 13 years!

160 GW → 4.8 Q



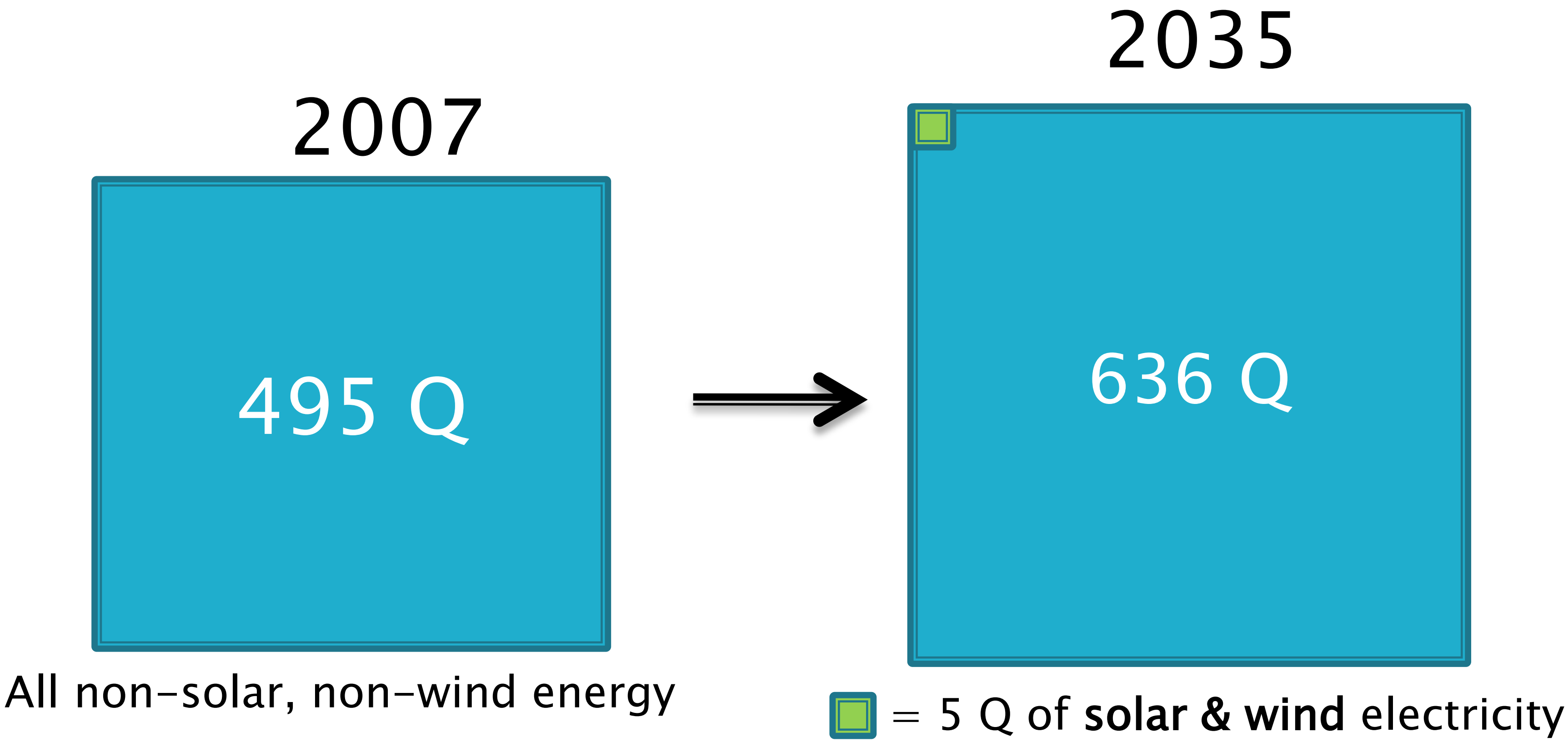
1996 2009

Source: Travelers Energy Project Financing
www.travelerscapital.com/wind.aspx

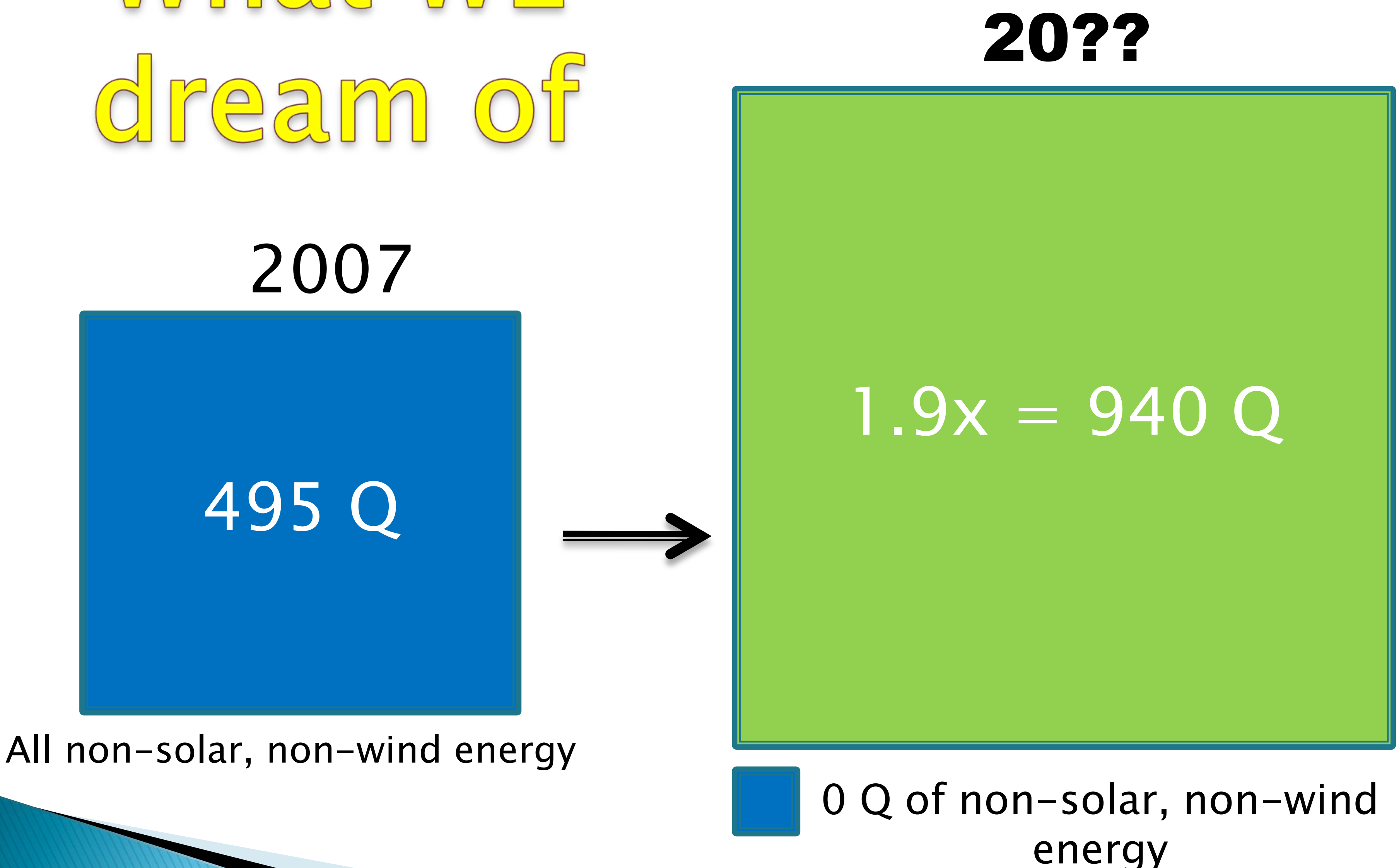
Notice that current rates of growth in Solar and Wind far outperform the DOE's predictions!

What's been happening?

What U.S. Dept. of Energy Anticipates



What WE dream of



How much power will we need in 20-40 years?

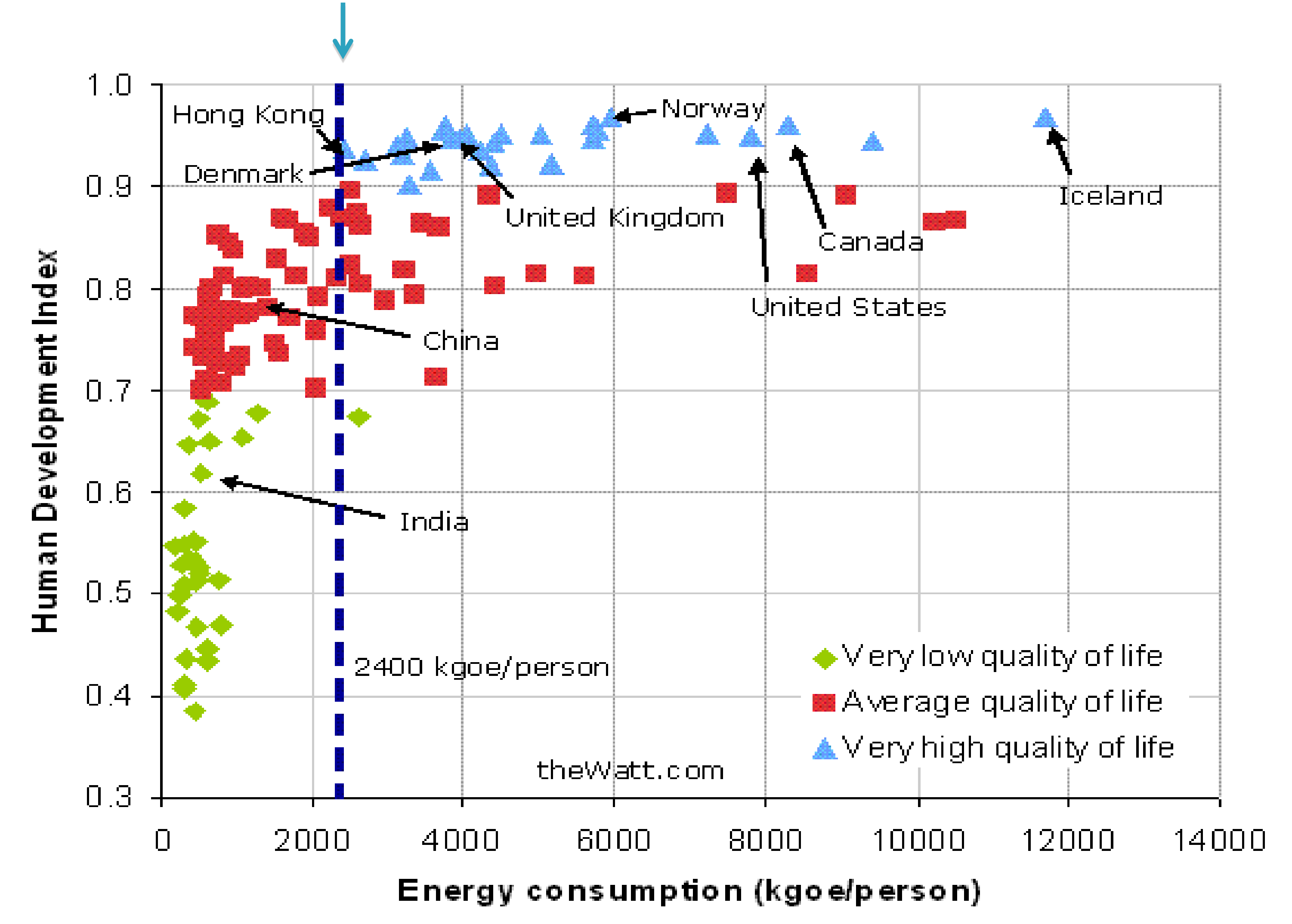
Requirement:
Enough for everyone to have high "quality of life."

- "high quality of life" = 3.5 kW **per capita** (Smil, 2008)
  - U.S.: 11.2 kW
  - Germany: ~6 kW
  - China: ~2 kW
  - India: ~1 kW

Most of the world today is suffering from energy poverty.

- In 2050, we'll need **2.0x** the current power (assuming pop. of 9.3 B)

Smil (2003, 2008) estimates a minimum requirement of 3.5 kilowatt per capita for high HDI, in comparison to 3.2 kilowatts per capita shown here (converted units):



Note: Energy consumption shown above is *per year*

More on calculation …

Assuming a minimum of 3.5 kilowatt per capita necessary for highest achievable quality of life, then x 7 billion people would require *a global power capacity of 24.5 TW or 1.5 x the present capacity of 16 TW.*
(1 Tera Watt (TW) = 10^{12} watts)

Hence, while the U.S. and several other countries need to reduce their energy consumption, ***most of the Global South requires a significant increase to achieve "state of the art/science" quality of life.***

But a shift to wind and solar-generated electricity as an energy source could reduce the required power level by 30% once a global system is created….
(Jacobson and Delucchi, "A Path to Sustainable Energy by 2030", Nov. 2009 *Sci. Amer.* "For example, only 17 to 20 percent of the energy in gasoline is used to move a vehicle (the rest is wasted as heat), whereas 75 to 86 percent of the electricity delivered to an electric vehicle goes into motion.")

How do we do this?

2007

495 Q

All non-solar, non-wind energy

Generate S–W Power Capacity in two ways:

(1) Use a small fraction of current FF to build S–W (f_{FF})

(2) Invest fraction of S–W to make more S–W infrastructure (f)

In other words

(1) Use to make

(2) Use some to make more

In end, count up (and use in self-sustaining fashion)

& get rid of all

How long will the transition take?

The details

2007

How much FF?

(1) Use to make — Call it f_{FF}

(note: this is a % of the current FF, annually, leaving out nuclear & current “renewables”)

(2) Use some to make more

How much RENEW?

Call it f

In end, count up and get rid of all

Note that f_{FF} and f are governed by policy decisions.

How long will the transition take?

This depends on four variables

f_{FF} = fraction of fossil fuels used annually (to create renewable power capacity)

TWEAK THESE!

f fraction of renewable power reinvested (to create new renewable power capacity)

policy

E_{out}/E_{in} = EROEI = energy produced over the energy input (to create renewable infrastructure)

20

= 10 – 40 (Schleisner, 2000 & many others)

L 20 = lifespan of renewable infrastructure

= 20 – 30 yrs (Sandia Labs, National Wind & others)

from literature

The Transition

2007

495 Q

All **non**-solar, non-wind energy

20??

2.0x = 990 Q

All solar (sun & wind) energy

OUR MODEL

Inputting some FF (f_{FF}) and reinvesting some RE (f):

(1) $d(P_{RE})/dt = [(M/L)(f)(P_{RE})] + [(M/L)(f_{FF})(P_{FF})];$ (M = EROEI)

This differential equation's solution is:

(2) $P_{RE} = (f)^{-1}(f_{FF})(P_{FF})[e^{[(f)(M/L)(t)]} - 1]$

For, beyond 20 years (no FF):

(7) $d(P_{RE})/dt = (f)(M/L)(P_{RE}) - (f_{FF})(P_{FF})(M/L)(e^{[(f)(M/L)(t-L)]})$

This has a solution of:

(8) $P_{RE} = [(f)(M)(L) + (L)(e^{(f)(M)}) - (f)(M)(t) - L]$

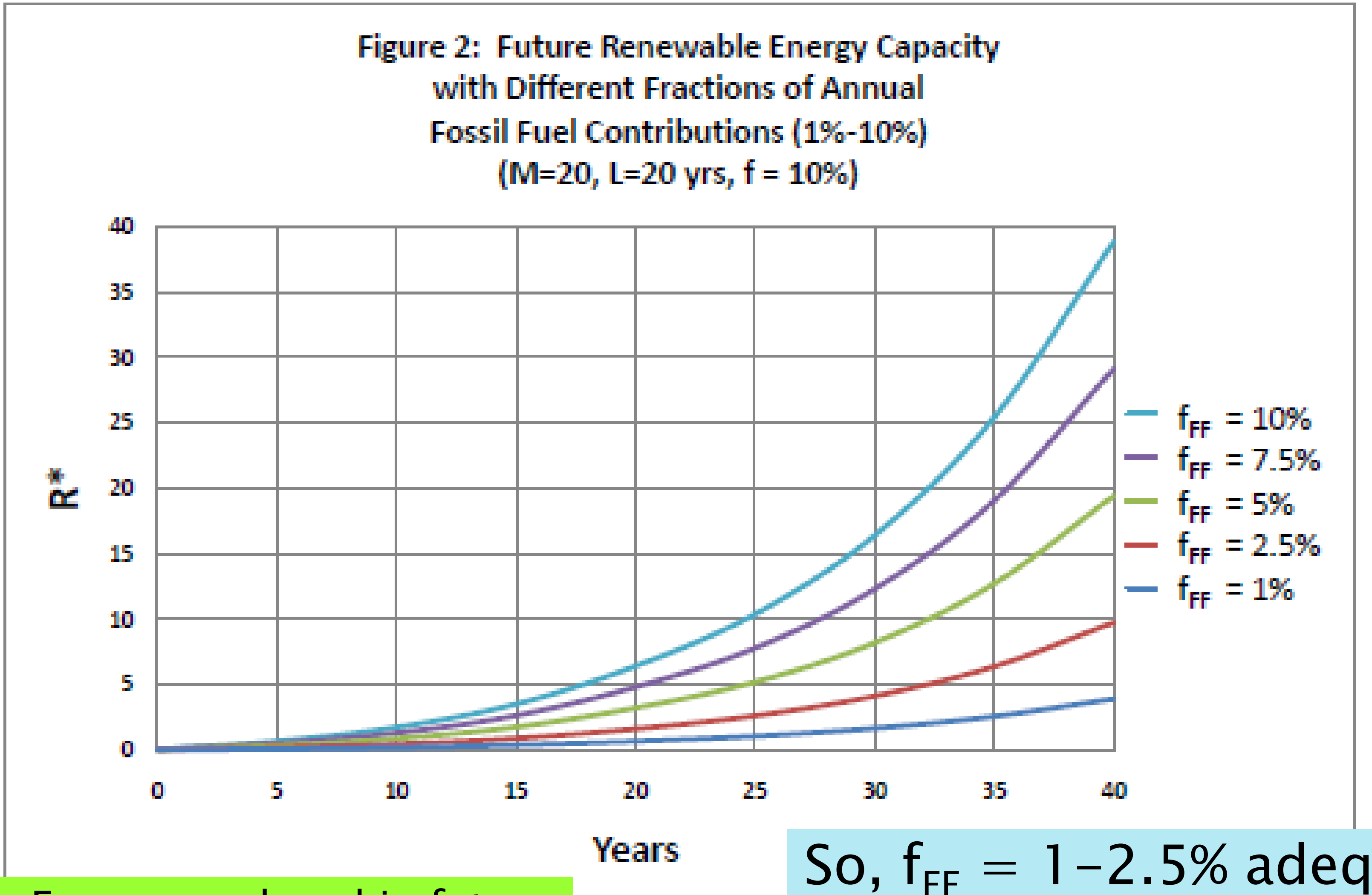
$[(fL)^{-1}(f_{FF})(P_{FF})e^{[(f)(M/L)(t-L)]}]$

Our model is conservative.

- EROEI & L values used are on low end of spectrum.
- All technologies used are currently available ones.
- No energy conservation programs/efforts are considered.

LET'S SEE SOME RESULTS…

How much FF input is needed annually to create a self-sustaining solar economy?



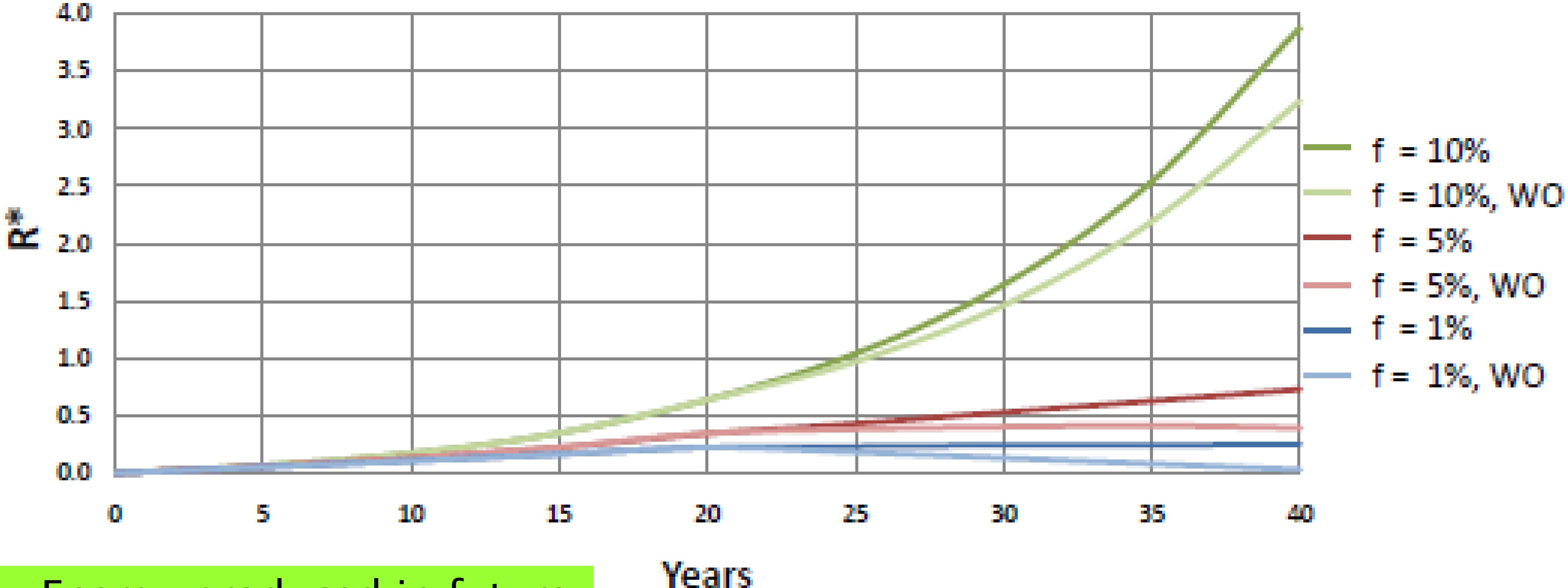
$R^* = \frac{\text{Energy produced in future}}{\text{Energy produced today}}$

So, f_{FF} = 1–2.5% adequate.

It can happen in 20–30 yrs!

How much reinvestment of RE is needed?

Figure 4: Future Renewable Energy Capacity with Different Fractions of Annual Renewable Energy Contribution (1%-10%) with and without (WO) FF after t=20 yrs ($M=20$, $L=20$yrs, $f_{FF}=1\%$)



$$R^* = \frac{\text{Energy produced in future}}{\text{Energy produced today}}$$

So, $f>5\%$ necessary, pick $f=10\%$.

Put these values into our "solar" calculator.

@ www.solarutopia.org

Solar Calculator

EROI for new RE (**M**): **20**

fraction of RE reinvested in new RE (**f**): **0.1**

fraction of FF invested in new RE (**f_{FF}**): **0.02**

	L = 15 years		L = 20 years		L = 25 years	
t (years)	**R***		**R***		**R***	
0	0.0		0.0		0.0	
5	0.2		0.1		0.1	
10	0.6		0.3		0.2	
15	1.3	**no F_{ff}↓**	0.7		0.5	
20	2.4	2.2	1.3	**no F_{ff}↓**	0.8	
25	4.4	3.8	2.1	1.9	1.3	**no F_{ff}↓**
30	7.8	6.5	3.3	2.9	1.9	1.8
35			5.1	4.4	2.8	2.5
40			7.8	6.5	3.9	3.4
45					5.6	4.7
50					7.8	6.5

OUR SOLAR CALCULATOR

Two components to Transition

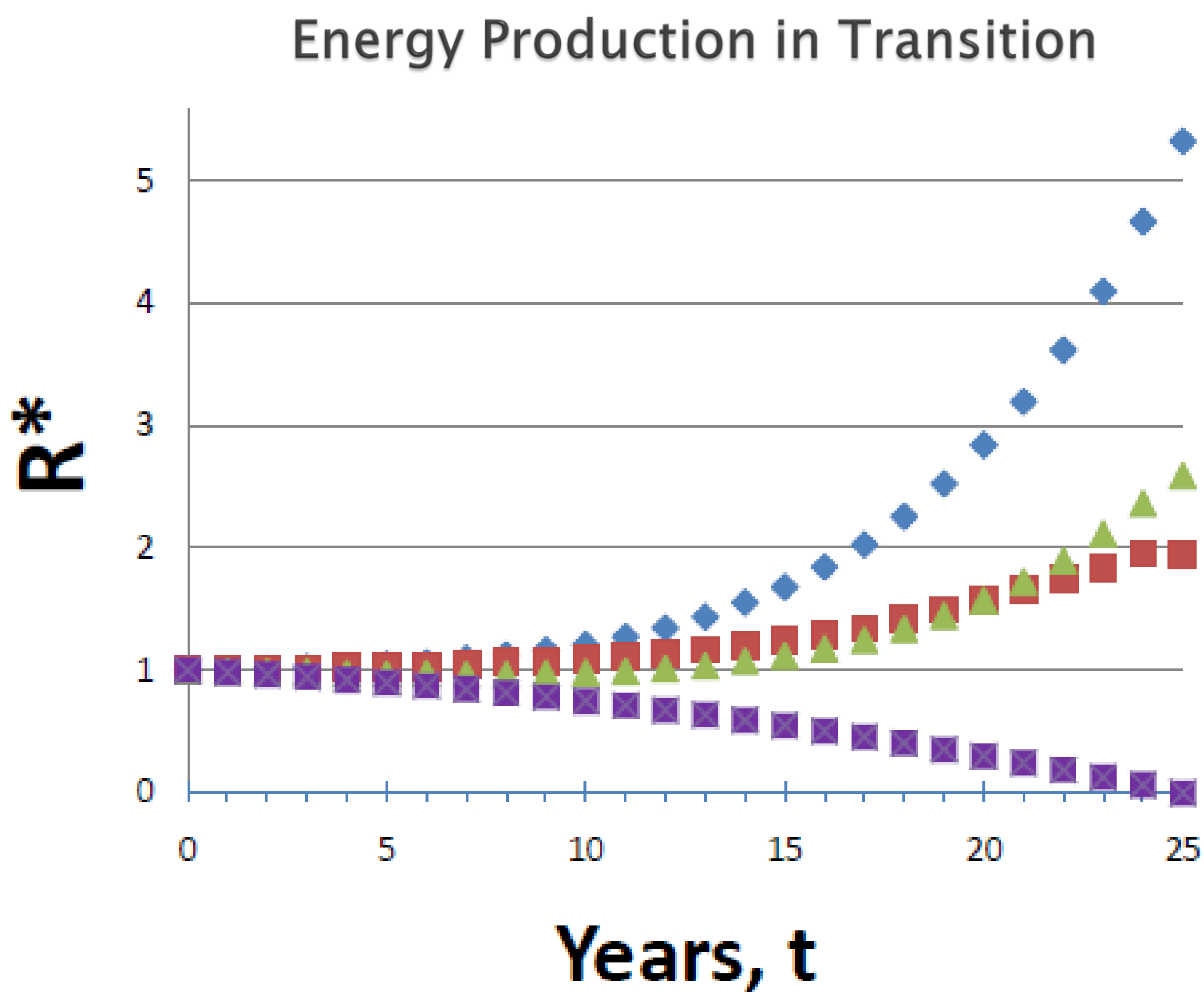
(1) Increase RE infrastructure until it provides sustainable levels of energy.

(2) Decrease FF contributions until they are no longer necessary.

MEANWHILE….

- Provide an increasing number of humans with sufficient energy needs.
- Increase energy conservation efforts for those with excess.

Do we have enough Fossil Fuel? (for Transition)



How much FF is this?

7 ZJ,
~40% of proven petroleum reserves
(no fracked gas or tar sands oil)
(Ahlbrandt et al., 2006)

$$R^* = \frac{\text{Energy produced in future}}{\text{Energy produced today}}$$

So, it is this simple?

Complications & objections:

- Intermittency of solar & wind
- Location of solar and wind (baseload)
- Insufficient amounts of rare earth metals
- Political will and determination
  - Where is the (complementary) economic model?
  - Big oil/gas/coal/nuclear won’t let this happen!

We must start Transition soon!

Gemasolar plant, near Seville, Spain
19.9 MW and 2,650 heliosat
(powers ~25,000 homes on 457 acres)

Questions
&
Reactions

In case there is any doubt about getting around with electricity?

- Galesburg , IL (1912)