Fueling the energy transition
The net energy perspective
Disclaimer:

• I’m a physical scientist, not an economist, I think of energy as a currency.

• When I use any of these words:
  – “cost”, “spend”, “buy”,
  – “cheap”, “expensive”
  – “surplus”, “deficit”, “subsidy”,
  – “debt”, “profit”,
  – “budget”, “invest” “afford”

I am talking in terms of energy
Outline

Motivation

Background
- Net energy metrics
- Why is dynamic perspective important?

Dynamic net energy analysis (NEA)
- PV industry
- Wind industry
- Energy storage
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Dynamic net energy analysis (NEA)
   ▪ PV industry
   ▪ Wind industry
   ▪ Energy storage
Energy demand could double 2000-2050

PROJECTED GLOBAL ENERGY DEMAND TO 2050
million barrels of oil equivalent a day

Source: Shell analysis, January 2012
Energy demand could double 2000-2050

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Source: Shell analysis, January 2012
Burning fossil fuels leads to climate change
Motivation

• Need to transition to affordable, accessible, sustainable, and low-carbon energy technologies
  – These are currently small proportion of our energy system (less than 15%)

• Rapid scale up of these technologies is needed to:
  – replace current system $\sim 15 \times 10^{12}$ W (TW)
  – and meet demand growth ($\sim 10$ TW?)

Which transition pathways are more feasible?
How fast can we transition?
Outline

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Energy flows for power plant, e.g. PV system
Net energy depends on two factors:

- **Energy inputs** – how much energy is required to deploy and run each unit of power capacity

  - Cumulative Energy Demand (CED) \[ \frac{kWh}{W_p} \]
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- **Energy output** – how much energy does each unit of capacity produce?
  
  - Capacity factor \[ \frac{W_{avg}}{W_p} \]
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- **Energy output** – how much energy does each unit of capacity produce?
  - Capacity factor \[
  \left[ \frac{W_{avg}}{W_p} \right]
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Typical values:
- Nuclear: 90%
- Coal: 80%
- Hydro: 40%
We can now define useful ‘net energy’ metrics

• **Energy return ratios:**
  – How many times over will our energy investment pay back?
  – e.g. energy-return-on-investment (EROI);
We can now define useful ‘net energy’ metrics

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Static vs. dynamic analysis

• Many life cycle metrics such as energy return on investment (EROI) do not show the costs of rapid scale-up or transition to alternative energy sources
Static vs. dynamic analysis

- Many life cycle metrics such as energy return on investment (EROI) do not show the costs of rapid scale-up or transition to alternative energy sources.

- **Timing** of material and energy flows is important
  - Most renewables require ‘up-front’ payment of majority of energy costs
  - Fossil fuels typically have larger operating costs
Importance of dynamic perspective

Energy flows for an industry growing at 100% per year

EPBT = 2 yrs
Importance of dynamic perspective

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EPBT = 2 yrs

YEAR 2
Importance of dynamic perspective

Energy flows for an industry growing at 100% per year

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Energy flows for an industry growing at 100% per year

EPBT = 2 yrs

Industry operates at energy ‘deficit’
Zooming out to longer time-scale

NET POWER [GJ/yr]

OUT PUTS

INPUTS

Gross Output

Gross Input

time (decades)
Zooming out to longer time-scale

• A fraction of gross output is re-invested for industry growth
Zooming out to longer time-scale

- Growing industry requires ‘start-up capital’…
Zooming out to longer time-scale

• …which it later ‘pays back’
Zooming out to longer time-scale

• …which it later ‘pays back’
Moving into log-log space

- Fractional re-investment may be greater than 100%
Summary

The faster the growth rate, the more energy is consumed by the industry to fuel its own growth.

If \( f > 100\% \) the industry requires an energy subsidy.
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– Why is dynamic perspective important?

Dynamic net energy analysis (NEA)

- PV industry
- Wind industry
- Energy storage
Energy balance of the PV industry

Research question:

“Is the PV industry a net electricity provider?”

Put another way:

“Does the PV industry consume more electricity than it produces?”
Energy balance of the PV industry

• To perform this analysis, we need three pieces of information:

  – Industry growth rate, \( r \left[ \frac{\text{%}}{\text{yr}} \right] \)

  – Cumulative energy demand, \( CED \left[ \frac{kWh}{W_p} \right] \)

  – Capacity factor (or load factor), \( \kappa \left[ \frac{W_{avg}}{W_p} \right] \)

PV industry is growing rapidly

Average growth 2000-2010
40% per year

CED – energetic cost for PV: meta-analysis

Dale & Benson (2013) Environmental Science & Technology, 47(7) 3482-3489
Energy inputs to PV – energy learning curves

CED [kWh(e)/W]

LR = 14-20%

Learning is reducing the energetic cost of PV deployment

Dale & Benson (2013) Environmental Science & Technology, 47(7) 3482-3489
Global PV capacity factor

Dale & Benson (2013) Environmental Science & Technology, 47(7) 3482-3489
Net energy landscape

Net energy trajectories for CdTe PV

Net energy trajectories for all PV technologies

Technologies with lower CED can grow at a faster rate

Conclusions

- The PV industry currently consumes around 90% of its own output.
  - This is fine while the industry is a small proportion of the overall energy sector
  - We need to continue to reduce the energetic cost of deploying PV systems

- Technologies with lower CED can grow at a faster rate and still deliver energy surplus – faster transition
Dynamic NEA of the wind industry
Dynamic NEA of the wind industry

• Again, we need three pieces of information to perform the analysis:
  \[ r \]
  
  – Industry growth rates, \[ \%/\text{yr} \]
  \[ \kappa \]
  
  – Capacity factor (or load factor) of wind systems, \[ \% \]
  \[ CED \]
  
  – Energetic cost (CED) of wind systems, \[ \text{kWh}_e/\text{W}_p \]
Wind industry has also been growing rapidly

Average growth 2000-2010
40% per year

Wind is less energy intensive than PV
Wind has a higher capacity factor.
Net energy trajectory for wind technologies

Wind supplies far more net energy to society

Conclusion

• Wind has lower CED *per unit capacity* than PV.

• Wind also has a higher capacity factor than PV.

• Currently consumes around 5-20% of its own output

• Allows for more rapid industry scale-up (>300 %/yr)
What about storage?
What about storage?

• Storage may be an important means to integrate intermittent renewable generation

• How much energy storage can the PV and wind industries ‘afford’ to deploy before running an energy deficit?

Pumped Hydro - PHS

Compressed Air - CAES

Battery Storage
Geologic storage ‘costs’ less than batteries

CdTe can ‘afford’ around 24 hours of storage


Slowing growth ‘buys’ more storage
CdTe can ‘afford’ around 24 hours of storage

Other PV has trouble ‘affording’ storage

Wind can ‘afford` storage more easily.

Conclusions

• The PV industry can ‘afford’ to buy up to 24 hours of energy storage

• Wind can ‘afford to buy’ over 72 hours of storage

• There are benefits to combining generation + storage technologies with low CED, e.g. wind + CAES
Implications of dynamic perspective

• Full lifecycle metrics cannot highlight timing of energy and material flows
• Rapid scale-up can mean that industries operate at an ‘energy deficit’
• Reducing CED should be an explicit goal of technology development
• Low CED systems can:
  – provide greater net energy surplus to society
  – enable higher growth rates – faster transition
Final thoughts

• Net energy provides a useful lens through which to view the world.

• It is useful for policy making and planning for a sustainable future.

• There is definite benefit to society of energy technologies with low energetic cost.

• More work needs to be done on reducing the energetic cost of renewables and storage technologies.
Acknowledgements:

• Thank you very much for inviting me to speak with you

• Thanks to GCEP for funding this research

• Thanks to Prof. Sally Benson, Dr. Richard Sassoon, Prof. Adam Brandt, Dr. Charles Barnhart for very fruitful and enlivening discussions


Growth rate and EPBT inversely related

There is a relationship between

- Industry growth rate, $r$ [% per yr]
- Energy payback time, $EPBT$ [yr]
- Fractional re-investment, $f$ [%]

\[ r = \frac{f}{EPBT} \]
Growth rate and EPBT inversely related

- For \( f = 100\% \)

\[
r = \frac{100\%}{EPBT}
\]
Growth rate and EPBT inversely related

- For \( f = 100\% \)

\[
\begin{align*}
r &= \frac{100\%}{EPBT} \\
&= \frac{100\%}{2} = 50\%
\end{align*}
\]
Fractional re-investment need not be 100%

\[ r = \frac{f}{EPBT} \]
Lower fractional re-investment slows growth

\[ r = \frac{f}{EPBT} = \frac{60}{2} = 30\% \]
If an industry is in energy deficit...
If an industry is in energy deficit…

- It can slow its growth rate…
If an industry is in energy deficit...

• ...reduce the EPBT...
If an industry is in energy deficit…

• …or both
CED – energetic cost for PV

- Crystalline silicon makes up 90% of installed capacity
CED – energetic cost for PV

- Crystalline silicon makes up 90% of installed capacity
- Silicon production is energy intensive…
CED – energetic cost for PV

• ...and that’s just the first step!

Poly-Si  Ingot  Wafer  Cell  Panel  System
CED – energetic cost for PV

• …and that’s just the first step!

• Financial costs ≠ energy costs

FINANCIAL COST

- Polysilicon: 12%
- Ingot: 6%
- Wafer: 9%
- Solar cell: 14%
- Solar panel: 25%
- System: 34%

Swanson (2011)

ENERGY COST

- Polysilicon: 21%
- Ingot & Wafer: 36%
- Solar cell: 11%
- Solar panel: 19%
- System: 13%

Alsema (2011)
CED – energetic cost for PV: meta-analysis

Kreith (1990)
Prakash (1995)
Kato (1997)
Keolian (1997)
Alsema (2000)
Frankl (2001)
Knapp (2001)
Mathur (2002)
GEMIS (2002)
Gürzenich (2004)
Krauter (2004)
Battisti (2005)
Fthenakis (2006)
Muneer (2006)
Mason (2006)
Kannan (2006)
Mohr (2007)
Pacca (2007)
Raugei (2007)
Ito (2008)
Stoppato (2008)
Roes (2009)
Fthenakis (2009)
Raugei (2009)
Zhai (2010)
Nishimura (2010)
Held (2011)
Laleman (2011)
PV learning curves – decreasing financial cost

• Learning rate (LR) defined as:
  – fractional decrease in costs per doubling in production

LR = 19%

Learning due to:
• wafer thickness
• wire sawing
• efficiency
• light-trapping

Swanson (2011)
Extrapolating into the future

• We have historic data from 2000-2012

• We want to model the growth of the PV industry out to 2020

• We need to account for uncertainty in:
  – growth rate
  – capacity factor and
  – energetic cost (CED)
Dealing with uncertainty – Monte Carlo simulation

### Parameters for Monte Carlo simulation

<table>
<thead>
<tr>
<th>Technology</th>
<th>Growth rate [%/yr]</th>
<th>Capacity factor [%]</th>
<th>Initial CED [kWh(e)/Wp]</th>
<th>Learning Rate [dmnl]</th>
</tr>
</thead>
<tbody>
<tr>
<td>sc-Si</td>
<td>56 ± 2.8</td>
<td>12 ± 3</td>
<td>55.8 ± 10</td>
<td>0.18 ± 0.02</td>
</tr>
<tr>
<td>mc-Si</td>
<td>50 ± 2.5</td>
<td>12 ± 3</td>
<td>50.7 ± 10</td>
<td>0.20 ± 0.02</td>
</tr>
<tr>
<td>Ribbon</td>
<td>32 ± 1.6</td>
<td>12 ± 3</td>
<td>12.9 ± 10</td>
<td>0.14 ± 0.02</td>
</tr>
<tr>
<td>a-Si</td>
<td>48 ± 2.4</td>
<td>12 ± 3</td>
<td>26.7 ± 10</td>
<td>0.14 ± 0.02</td>
</tr>
<tr>
<td>CdTe</td>
<td>133 ± 66.5</td>
<td>12 ± 3</td>
<td>13.9 ± 10</td>
<td>0.15 ± 0.02</td>
</tr>
</tbody>
</table>

- a-Si values are assumed from a-Si.
- CdTe values are assumed from CdTe.

Cumulative Production [MW]

Energy Cost [kWh(e)/Wp]
Results: power production [TWh/yr]