Renewable energies
and large scale electricity storage

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World energy use; Global Energy Assessment 2012

525 EJ = 525 \times 10^{18} \text{J} = 86 \text{ billion barrels of oil equivalent}

http://www.iiasa.ac.at/
Main forms of renewable energy worldwide:

**Future:**
- Solar power
- Wind power
- Biomass
- Hydropower

**Now:**
- Biomass
- Hydropower
- Wind power
- Solar power
Solar energy
How to collect this energy?

- Photovoltaic devices (‘solar cells’) for electricity generation
- Solar thermal energy

Solar cells

Focusing mirrors heating liquid in tubes
Solar power

Justin Quinnell, Pinhole photography from mid winter to mid summer
Hourly variation of irradiance on a horizontal surface: $G_h$

(a) Clear day

(b) Cloudy day
Source: European Photonics Industry Consortium (EPI C)
1,000,000 MW = 100 GW installed power
Global wind resources

Annual 50m Wind Speed
July 1983 – June 1993

GEOS-1 satellite view of global wind speeds
Global Wind Power Cumulative Capacity (Data: GWEC)

Global Cumulative Capacity (GW)

- 1996: 6.1 GW
- 1997: 7.6 GW
- 1998: 10.2 GW
- 1999: 13.6 GW
- 2000: 17.4 GW
- 2001: 23.9 GW
- 2002: 31.1 GW
- 2003: 39.4 GW
- 2004: 47.6 GW
- 2005: 59.1 GW
- 2006: 74.1 GW
- 2007: 93.8 GW
- 2008: 120.3 GW
- 2009: 158.9 GW
- 2010: 197.6 GW
- 2011: 238.4 GW
- 2012: 280 GW

Installed larger than prediction
Renewables variation and energy storage

From Mulder, J. Renewable and Sustainable Energy 2014
http://dx.doi.org/10.1063/1.4874845
Renewables…

Proposed energy super-grid
- Solar (CSP)
- Solar (PV)
- Biomass
- Geothermal
- Hydro
- Wind

Light switch on continents!
(day/night and summer/winter)

DESERTEC plan

0°
Most people live on the Northern hemisphere above 20°

Population Density

Global
Large area still shows large wind power fluctuations
Seasonal variations

Daily variations

Energy use 2012

Dutch energy use: 2.8 MW/km² (excluding sea EEZ)
German: 1.2 MW/km²
World: 33 kW/km² (entire globe)

Source: 75% fossil energy
Where do we plan to go from here?

EU roadmap:
80% less CO₂ by 2050 →
≈ No more fossil power

Somewhat less ambitious approach:

Scenario Global Energy Assessment 2012
World energy use; Global Energy Assessment 2012

525 EJ = 525\times 10^{18} J = 86 billion barrels of oil equivalent

http://www.iiasa.ac.at/
Varying output of renewables on an extended grid

2050

summer

winter

avg.

avg.
Future sun + wind compared to electricity use

Renewable peak power becomes large compared to peak use
Did I miss something?

Electrification
Load shifting
Energy storage!
From Mulder, J. Renewable and Sustainable Energy 2014
http://dx.doi.org/10.1063/1.4874845
What to do with too much electricity?
- use electricity for more applications (EV, heating, …)
- match supply & demand by long/short term storage

2050:
Short term: 0.2 EJ
NL ~ 44 kWh/house

Long term: 30 EJ
6% WEU
2050:
Short term: 0.2 EJ
NL ~ 44 kWh/house

2030: 10 EJ = 2800 TWh
2050: 29 EJ = 8000 TWh
With storage one can replace fossil powered capacity

Note EU Roadmap: -80% CO₂ in 2050
Current energy neutral approach: storage capacity is just powering up and down the fossil grid.

Future: there is too much renewable power to do this.

Note: “NL-energieakkoord”: 12.5GW wind power while we use on average 8GW electric power from grid
Price effects in Germany during the day:

- Reducing daily price for renewables
- Reducing daily price for fossile power
- High investments in parallel infrastructure

→ Deteriorating earnings at higher cost (for all)
IEA World Energy Investment Outlook 2014, just released:

- From 2000: most installed capacity is renewable in EU
- From 2008: 200TWh renewable energy replaced fossil energy

*The total electricity use in the EU was 3126 TWh in 2012, so a change of 300TWh is ~10% change*
Large scale energy storage is required for economic renewable energy implementation.
Energy densities of storage technologies

- Energy density (kWh m⁻³)
- Energy density (kWh kg⁻¹)

Graph showing energy densities of various storage technologies, including electrochemical and inertia, hydrogen storage, flywheel, Li-ion battery, and others. The graph compares energy densities in two different scales.
Current energy storage?

We run on fossil fuels!

• 78% of current global energy use comes from oil, coal, and natural gas

• The flow of energy can essentially be regulated on demand by a valve
## Solutions for large EJ scale energy storage?

<table>
<thead>
<tr>
<th></th>
<th>capacity</th>
<th>efficiency</th>
<th>Long term</th>
<th>Short term</th>
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<tbody>
<tr>
<td></td>
<td>EJ scale</td>
<td>e$^-$ → e$^-$</td>
<td></td>
<td></td>
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<tr>
<td>Hydropower</td>
<td>- -</td>
<td>++</td>
<td>-</td>
<td>++</td>
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<tr>
<td></td>
<td></td>
<td>0.82</td>
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<tr>
<td>Compressed air</td>
<td>- -</td>
<td>+</td>
<td>-</td>
<td>++</td>
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<tr>
<td></td>
<td></td>
<td>0.75$^2$</td>
<td></td>
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<tr>
<td>Batteries</td>
<td>-</td>
<td>++</td>
<td>- -</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.85$^2$</td>
<td></td>
<td></td>
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<tr>
<td>Hydrogen under-ground storage</td>
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<td>-/-</td>
<td>++</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>0.65$^2x0.85^2$</td>
<td></td>
<td></td>
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<tr>
<td>NH$_3$ (l)</td>
<td>++</td>
<td>- -</td>
<td>++</td>
<td>+</td>
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<tr>
<td></td>
<td></td>
<td>0.3x0.65</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C$_n$H$_m$O$_p$</td>
<td>++</td>
<td>---</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CO$_2$ from air?</td>
<td></td>
<td></td>
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Solutions for large EJ scale energy storage?

<table>
<thead>
<tr>
<th>Method</th>
<th>Capacity</th>
<th>Efficiency</th>
<th>Long term</th>
<th>Short term</th>
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<tr>
<td>Hydropower</td>
<td>-</td>
<td>+</td>
<td>++</td>
<td>-</td>
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<tr>
<td>Compressed air</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>++</td>
</tr>
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<td>-</td>
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<td>++</td>
</tr>
<tr>
<td>Hydrogen underground storage</td>
<td>-</td>
<td>++</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>NH$_3$ (l)</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>C$<em>{n}$H$</em>{m}$O$_{p}$</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

*Note: The values represent the relative performance of each method.*
Storage options for large scales: to be developed (!)

- **batteries**
  - For the short term only (low J/€)
  - Requires long life, cheap batteries

- **H₂**
  - Requires large scale storage method itself
  - Requires cost reduction
  - Can partially be fed in gas-grid
    (max 10% ~5GW in Germany, limited compared to current 22GW PV record)

- **CₖHₙOₘ**
  - Synthetic conventional fuels
  - Requires a carbon source (CO₂ from air)

- **NH₃**
  - Is already produced & stored at large scale, but not from renewables.
  - In industrial environment only (poisonous, safety).
  - Low efficiency, requires new synthesis routes

- **heat**
  - Conversion losses may be recovered as heat, CHP
Hydropower and storage?

Itaipu dam, Paraguay, Brazil, 14.0 GW
Combination of hydro power with energy storage
Combination wind and water power in ‘Energy Island’

Idea: - use windpower to generate electricity
- use peaks in windpower to pump out water of artificial lake
- When demand of electricity peaks: use water flow into lake to generate electricity

20GWh
2.5 G€ (?)
Pumped hydropower at sea

Capacity: 20GWh → ~100 units needed for 1 day of energy NL
Biofuels can be stored

- Sugarcane
- Rapeseed
- flaxseed
- Soybeans
- Elephant Grass
- Palm oil
Switch grass

Poplar trees

and Algae in water
### Table 1: Oil producing crops (Adapted from Tickell, 2000)

<table>
<thead>
<tr>
<th>Plant</th>
<th>Latin Name</th>
<th>Gal Oil/Acre</th>
<th>Plant</th>
<th>Latin Name</th>
<th>Gal Oil/Acre</th>
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</thead>
<tbody>
<tr>
<td>Oil Palm</td>
<td>Elaeis guineensis</td>
<td>610</td>
<td>Rice</td>
<td>Oriza sativa L.</td>
<td>85</td>
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<tr>
<td>Macauba Palm</td>
<td>Acrocomia aculeata</td>
<td>461</td>
<td>Buffalo Gourd</td>
<td>Cucurbita foetidissima</td>
<td>81</td>
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<tr>
<td>Pequi</td>
<td>Caryocar brasiliense</td>
<td>383</td>
<td>Safflower</td>
<td>Carthamus tinctorius</td>
<td>80</td>
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<tr>
<td>Buriti Palm</td>
<td>Mauritia flexuosa</td>
<td>335</td>
<td>Crambe</td>
<td>Crambe abyssinica</td>
<td>72</td>
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<tr>
<td>Oiticia</td>
<td>Licania rigida</td>
<td>307</td>
<td>Sesame</td>
<td>Sesamum indicum</td>
<td>71</td>
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<tr>
<td>Coconut</td>
<td>Cocos nucifera</td>
<td>276</td>
<td>Camelina</td>
<td>Camelina sativa</td>
<td>60</td>
</tr>
<tr>
<td>Avocado</td>
<td>Persea americana</td>
<td>270</td>
<td>Mustard</td>
<td>Brassica alba</td>
<td>59</td>
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<tr>
<td>Brazil Nut</td>
<td>Bertholletia excelsa</td>
<td>245</td>
<td>Coriander</td>
<td>Coriandrum sativum</td>
<td>55</td>
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<tr>
<td>Macadamia Nut</td>
<td>Macadamia terniflora</td>
<td>230</td>
<td>Pumpkin Seed</td>
<td>Cucurbita pepo</td>
<td>55</td>
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<tr>
<td>Jatropha</td>
<td>Jatropha curcas</td>
<td>194</td>
<td>Euphorbia</td>
<td>Euphorbia lagascae</td>
<td>54</td>
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<tr>
<td>Babassu Palm</td>
<td>Orbignya martiana</td>
<td>188</td>
<td>Hazelnut</td>
<td>Corylus avellana</td>
<td>49</td>
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<tr>
<td>Jojoba</td>
<td>Simmondsia chinensis</td>
<td>186</td>
<td>Linseed</td>
<td>Linum usitatissimum</td>
<td>49</td>
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<tr>
<td>Pecan</td>
<td>Carya illinoensis</td>
<td>183</td>
<td>Coffee</td>
<td>Coffea arabica</td>
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<tr>
<td>Bacuri</td>
<td>Platonia insignis</td>
<td>146</td>
<td>Soybean</td>
<td>Glycine max</td>
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<tr>
<td>Castor Bean</td>
<td>Ricinus communis</td>
<td>145</td>
<td>Hemp</td>
<td>Cannabis sativa</td>
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<tr>
<td>Gopher Plant</td>
<td>Euphorbia lathyris</td>
<td>137</td>
<td>Cotton</td>
<td>Gossypium hirsutum</td>
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<td>Piassava</td>
<td>Attalea funifera</td>
<td>136</td>
<td>Calendula</td>
<td>Calendula officinalis</td>
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<tr>
<td>Olive Tree</td>
<td>Olea europaea</td>
<td>124</td>
<td>Kenaf</td>
<td>Hibiscus cannabinus L.</td>
<td>28</td>
</tr>
<tr>
<td>Rapeseed</td>
<td>Brassica napus</td>
<td>122</td>
<td>Rubber Seed</td>
<td>Hevea brasiliensis</td>
<td>26</td>
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<tr>
<td>Opium Poppy</td>
<td>Papaver somniferum</td>
<td>119</td>
<td>Lupine</td>
<td>Lupinus albus</td>
<td>24</td>
</tr>
<tr>
<td>Peanut</td>
<td>Ariachis hypogaea</td>
<td>109</td>
<td>Palm</td>
<td>Erythra salvadorensis</td>
<td>23</td>
</tr>
<tr>
<td>Cocoa</td>
<td>Theobroma cacao</td>
<td>105</td>
<td>Oat</td>
<td>Avena sativa</td>
<td>22</td>
</tr>
<tr>
<td>Sunflower</td>
<td>Helianthus annuus</td>
<td>98</td>
<td>Cashew Nut</td>
<td>Anacardium occidentale</td>
<td>18</td>
</tr>
<tr>
<td>Tung Oil Tree</td>
<td>Aleurites fordii</td>
<td>96</td>
<td>Corn</td>
<td>Zea mays</td>
<td>18</td>
</tr>
</tbody>
</table>

1 gal/acre = 3.785 L per 4046.9 m² = 0.935 ml/m²

Maximum = 610 x 0.935 = 570 ml/m² for oil palm


ATTRA Publication
Biofuels are quoted as CO$_2$ neutral, however, processing energy and fertilizer inputs are required (!)

\[
\text{Sunlight + water + CO}_2 + \text{nutrition/fertilizers} = \text{Crops + O}_2
\]

\[
\text{Crops + harvesting + processing} = \text{Biofuels + water + CO}_2 + \text{fertilizers + waste}
\]

\[
\text{Biofuels + O}_2 = \text{Power + water + CO}_2 + \text{waste}
\]
To fulfill energy needs by biofuel alone one needs: $\frac{28.8}{412} = 7\%$ of the earths surface (which is impossible).
Biofuel challenges:

- Competition for land & food
- Conversion efficiency solar light to biofuel is small
- Biodiversity
- Efficiency: sunlight to biomass conversion is 0.2% efficient on average
Heat storage

• Cool building in summer with cold water from deep in the ground, put warm water deep in the ground
• In winter heat buildings with the warm water and cool down water layers again
• large reduction of heating demands in green houses
Storage media:
- water
- Phase change materials (solid-liquid)
Conclusions

- Renewables are growing fast
- Solar and wind power are expected to become dominant
- The grid can facilitate transport and trade of electricity but it can not (yet) provide storage on sufficient scale
- Electricity storage in batteries and fuels will become essential upon increasing renewables implementation