Solar energy in the context of energy use, energy transportation, and energy storage

David MacKay FRS
Cavendish Laboratory
University of Cambridge

www.withouthotair.com
How wide would the biofuel plantation be?
One lane of cars

60 miles per hour
30 miles per gallon
1200 litres of biofuel per hectare per year
80 metres car-spacing
How wide would the biofuel plantation be?

One lane of cars

60 miles per hour
30 miles per gallon
1200 litres of biofuel per hectare per year
80 metres car-spacing

= 8 kilometres wide
Glass Moor, Peterborough, Cambridgeshire

R.O. ID R00159RQEN
Current TIGC (kW) 16,000

Annual Summary

<table>
<thead>
<tr>
<th>Year</th>
<th>Annual TIGC (kW)</th>
<th>Annual ROCs (MWh)</th>
<th>Annual LF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>2003</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>2004</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>16,000</td>
<td>31,645</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>16,000</td>
<td>38,635</td>
<td>27.6</td>
</tr>
</tbody>
</table>

Turbine Summary

- Wind turbine model: REPower
- No of turbines: 8
- Size of turbine (kW): 2,000
- Rotor diameter (m): 82
- Hub height (m): 59

Average 4.4 MW from 2 km²
Power per unit area: 2.2 W/m²
Average 29 MW from 10.2 km²
Power per unit area: 2.8 W/m²
Farr windfarm

92MW Capacity

Average 27 MW from 8 km²
Power per unit area: 3.4 W/m²

Load factor 29.7%

photo by richard1151

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<th>Annual ROCs (MWh)</th>
<th>Annual LF (%)</th>
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<tr>
<td>2002</td>
<td>92,000</td>
<td>0</td>
<td></td>
</tr>
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<td>92,000</td>
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<td></td>
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<td>0</td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>92,000</td>
<td>519</td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>92,000</td>
<td>153,419</td>
<td>19.0</td>
</tr>
<tr>
<td>2007</td>
<td>92,000</td>
<td>239,520</td>
<td>29.7</td>
</tr>
</tbody>
</table>

Turbine Summary

Wind turbine model: Bonus 2.3
No of turbines: 40
Size of turbine (kW): 2,300
Rotor diameter (m): 30
Hub height (m):
Powers per unit area of British wind farms, v farm size
To get 17 kWh/d per person from wind (on average):
[all UK electricity, today]

One 2-MW turbine for every 700 people
Roughly 60-fold increase over today’s UK wind
Area of wind farms: roughly 7% of UK
Dr Emily Heaton is 5'4" (163 cm) tall

Photo provided by the University of Illinois
Plant power per unit area

- wood (commercial forestry)
- rape
- rape to biodiesel
- maize
- sugar beet
- short rotation coppice calorific value
- energy crops calorific value
- miscanthus to electricity
- switchgrass
- corn to ethanol
- wheat to ethanol
- jatropha

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sugarcane (Brazil, Zambia)

tropical plantations (eucalyptus)
tropical plantations*

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* assumes genetic modification, fertilizer application, and irrigation

For sources, see D J C MacKay (2008) Sustainable Energy - without the hot air
Solar electric (photovoltaic)

Data and photo by Jonathan Kimmitt - 25 sq m of panels

Power per unit area: 20 W/m²
Bavaria Solar Park: $5 \text{W/m}^2$; this picture shows 0.7 MW (average)
2.1 MW Tracking solar PV in Vermont, September:

Average 0.428 MW from 0.1 km² (2.1 MW capacity)
Power per unit area: 4.2 W/m²

Kilowatt hours (kWh)
16616.6 kWh

Data from www.allearthrenewables.com
installed June 2011  
cost $12M ($28 per average watt)  
average isolation 159 W/m² (Sept): 143 W/m² (annual)
Insolation data is 10-year average for Montpelier, VT (33 miles away)
Source: NASA - Surface meteorology and Solar Energy Data Set

Data from www.allearthrenewables.com

installed June 2011  cost $12M ($28 per average watt)  average insolation 158 W/m² (Sept); 143 W/m² (annual)
PV efficiencies

- Amorphous silicon
- Multi-crystalline silicon
- Single crystal silicon
- Sunpower WHT
- Sanyo HIP
- Suntech poly-crystalline
- Thin-film triple junction

Efficiency vs. irradiance graph:
- X-axis: Irradiance (W/sq m)
- Y-axis: Delivered power (W/sq m)
- Green line: Shockley-Queisser limit
- Yellow line: Triple-junction limit
All renewables are diffuse

**Power per unit land area**

- Wind: 2.5 W/m²
- Plants: 0.5 W/m²
- Solar PV panels: 4–20 W/m²
- Tidal pools: 3 W/m²
- Tidal stream: 8 W/m²
- Rain-water (highlands): 0.24 W/m²
- Concentrating solar power (desert): 15–20 W/m²

To make a difference, renewable facilities have to be country-sized

Nant-y-Moch by Dave Newbould
www.origins-photography.co.uk
CSP

Each blob: 1500 sq km; 44km diameter; 10 GW if 50% solar farm, at 15 W/sq m.

65 blobs: - 16 kWh/d/p x 1Gp
Yellow: 125 kWh/d/p for 1 billion people; Red: 125 kWh/d/p for 60 million people (assuming 15 W/m²)
Each blob: 1500 sq km; 44 km diameter; 10 GW if 50% solar farm, at 15 W/sq m.
65 blobs: - 16 kWh/d/p x 1 Gp
Andasol, Spain

10 W/m²
PS10, Solucar

5 W/m²

Photo by afloresm
HVDC transmission

Photos and diagrams: ABB

2GW -->

3.1GW, 1360km

Mozambique - South Africa

0.7GW, 580km
Finland - Estonia: One pair of cables transmit 350 MW

Photos: ABB
If we include the land for HVDC transmission...

<table>
<thead>
<tr>
<th>Description</th>
<th>Area</th>
<th>Power Density</th>
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<tr>
<td>CSP power density</td>
<td>15 W/m²</td>
<td>20 W/m²</td>
</tr>
<tr>
<td>40 GW (avg) of CSP</td>
<td>2700 km²</td>
<td>2000 km²</td>
</tr>
<tr>
<td>land for 50 GW (peak) HVDC</td>
<td>1500 km²</td>
<td>1500 km²</td>
</tr>
<tr>
<td>total area</td>
<td>4200 km²</td>
<td>3500 km²</td>
</tr>
<tr>
<td>net power density</td>
<td>9.5 W/m²</td>
<td>11.4 W/m²</td>
</tr>
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2 GW ->
Alternatively, power could be delivered as chemicals

40 GW = 2 tankers per day

Photo (c) by Kevin Quick
All renewables are diffuse

**Power per unit land area**

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<th>Source</th>
<th>Power (W/m²)</th>
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<td>2.5</td>
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<td>Tidal pools</td>
<td>3</td>
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<tr>
<td>Tidal stream</td>
<td>8</td>
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<tr>
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<td>15–20 W/m²</td>
</tr>
<tr>
<td>Solar HW panels</td>
<td>50 W(θ)/m²</td>
</tr>
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</table>
Solar HW

2 kWh/d per person
Electricity, gas, and transport demand; and fictional wind (assuming 33 GW of capacity), all on the same vertical scale.
Pumped storage

Dinorwig - 10 GWh energy; 2 GW maximum power
Seasonal heat stores

Especially for old buildings
Seasonal heat store, solar panel, and heat pump
Seasonal heat store, solar panel, and heat pump
6-month diffusion length of heat in rock is about 6m.

A 20-m cylinder, radius 6 m, can store 24 kWh/d * 6 months with a temperature increase of 3.4 C
BEAUFORT COURT:
RENEWABLE ENERGY SYSTEMS HEADQUARTERS

Net heat collected into storage every year: 12 MWh
Welcome to Drake Landing Solar Community.

The Drake Landing Solar Community (DLSC) is a master planned neighbourhood in the Town of Okotoks, Alberta, Canada that has successfully integrated Canadian energy efficient technologies with a renewable, unlimited energy source - the sun.

The first of its kind in North America, DLSC is heated by a district system designed to store abundant solar energy underground during the summer months and distribute the energy to each home for space heating needs during winter months.

The system is unprecedented in the World, fulfilling ninety percent of each home’s space heating requirements from solar energy and resulting in less dependency on limited fossil fuels.

The Government of Canada and its Canadian industry partners are proud to showcase Canadian solar thermal and energy efficient technologies in this one-of-a-kind community.
Detached garages with solar collectors on the roofs

Solar collector loop

Energy Centre with short-term thermal storage tanks

Borehole seasonal (long-term) thermal storage

District heating loop (below grade) connects to homes in community

Two-storey single-family homes
heat store: 37m deep, 35m wide

roughly 1 GWh(th) - roughly 100 kWh/d per dwelling, for 50 dwellings, for 100 days
Similar size and function to ice house!
International energy trade

In the 1890s Norway exported 340,000 tons of ice each year.

London Canal Museum
## Electricity storage costs

<table>
<thead>
<tr>
<th>Type of Storage</th>
<th>Plant $/kW</th>
<th>Storage $/kWh*</th>
<th>$ for 6 Hrs</th>
<th>Capital $/kWh</th>
<th>$/kWh**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isentropic Pumped Heat Storage</td>
<td>450</td>
<td>50</td>
<td>750</td>
<td>125</td>
<td>0.017</td>
</tr>
<tr>
<td>Pumped Hydro 1GW</td>
<td>600</td>
<td>37.5</td>
<td>825</td>
<td>138</td>
<td>0.019</td>
</tr>
<tr>
<td>Compressed Air Underground 300MW</td>
<td>580</td>
<td>1.75 + 146**</td>
<td>1467</td>
<td>244</td>
<td>0.033</td>
</tr>
<tr>
<td>Compressed Air Above ground 15MW</td>
<td>750</td>
<td>250 + 146**</td>
<td>3126</td>
<td>521</td>
<td>0.071</td>
</tr>
<tr>
<td>Na-Sulphur Batteries</td>
<td>500</td>
<td>350</td>
<td>2600</td>
<td>433</td>
<td>0.059</td>
</tr>
<tr>
<td>Flow Batteries</td>
<td>425</td>
<td>280</td>
<td>2105</td>
<td>350</td>
<td>0.048</td>
</tr>
<tr>
<td>Lead Acid Batteries</td>
<td>420</td>
<td>330</td>
<td>2400</td>
<td>400</td>
<td>0.055</td>
</tr>
</tbody>
</table>

* Assuming electricity stored is nil cost
** Compressed Air burns gas at ~100% efficiency due to the use of the pressurised gas. One kWh of gas currently costs $0.02. To get an equivalent storage cost, we capitalise the gas required for one discharge per day for 20 years = $146
*** Capital Cost per kWh divided by total hours used (assume 20 years life and 1 charge/discharge per day – 7300 hours)
Storage costs - assume $125 per kWh [optimistic?]

Solar system cost: $28k per average kW; (to compete, aiming perhaps for $10k per average kW?)

(6 cents per kWh, 20 years, no discounting, no maintenance)

installed June 2011

cost $12M ($28 per average watt)
Storage costs - assume $125 per kWh [optimistic?]

Solar system cost: $28k per average kW; (to compete, aiming perhaps for $10k per average kW?)

To keep 1 kW going for 12 hours of darkness, need 12 kWh of storage, which costs an extra $1.5k

To keep 1 kW going for 5 dull days, need 120 kWh of storage, which costs an extra $15k

So, for PV to deliver cost-competitive reliable electricity in a sometimes-cloudy location, we need two cost breakthroughs!
Can Solar Power Deliver?

Yes!

- especially, initially:
  - concentrating solar in deserts
  - solar thermal
  - low-cost photovoltaics matched to air-conditioning demand

But don't let's kid ourselves about

- the area required
- the need for PV to have further cost reductions
- the additional costs of intermittency
  - energy storage
  - transmitting energy large distances
2050 pathways

2050 Web tool

Energy flows ➤

Area used ➤

Embedded sector summaries ➤

2050-calculator-tool.decc.gov.uk
UK energy demand
TWh/yr of final energy

UK energy supply
TWh/yr of primary energy

UK greenhouse gas emissions
MtCO2e/yr

Domestic transport behaviour
1 2 3 4
Domestic transport electrification
1 2 3 4
Domestic freight
1 2 3 4
International aviation
1 2 3 4
International shipping
A B C D

Average temperature of homes
1 2 3 4
Home insulation
1 2 3 4
Home heating electrification
A B C D
Home heating that isn’t electric
A B C D
Home lighting & appliances
1 2 3 4
Electrification of home cooking
A B

Growth in industry
A B C
Energy intensity of industry
1 2 3
Commercial demand for heating and cooling
1 2 3
Commercial heating electrification
A B C D
Commercial heating that isn’t electric
A B C D
Commercial lighting & appliances
1 2 3 4
Electrification of commercial cooking
A B

Nuclear power stations
1 2 3 4
CCS power stations
1 2 3 4
CCS power station fuel mix
A B C D

Offshore wind
1 2 3 4
Onshore wind
1 2 3 4
Tidal and wave
1 2 3 4
Biomass power stations
1 2 3 4
Solar panels for electricity
1 2 3 4
Solar panels for hot water
1 2 3 4
Geothermal electricity
1 2 3 4
Hydroelectric power stations
1 2 3 4
Small-scale wind
1 2 3 4
Electricity imports
1 2 3 4

Land dedicated to bioenergy
1 2 3 4
Livestock and their management
1 2 3 4
Volume of waste and recycling
A B C
Marine algae
1 2 3 4
Type of fuels from biomass
A B C D
Bioenergy imports
1 2 3 4

Conventional power stations are built automatically to fill any shortfall in electricity supply. Coal, Oil and Natural Gas are

Geosequestration
1 2 3 4

2050 emissions will be 72% below 1990 levels.
International aviation and shipping emissions are not included in the UK’s 2050 target but are included here to enable emissions from all sectors to be considered.

Energy security
Storage, demand shifting & interconnection
1 2 3 4

If there are five cold, almost windless, winter days in 2050, then up to 27 GW of backup generation capacity will be required to ensure that electricity is always available.

In 2050, 40% of primary energy will be imported.
UK energy demand
TWh/yr of final energy

UK energy supply
TWh/yr of primary energy

UK greenhouse gas emissions
MtCO2e/yr

This pathway should meet the UK 2050 climate change target

~13 3GW power stations delivering ~280 TWh/yr

Geosequestration
2050 emissions will be 80% below 1990 levels.

Energy security
Storage, demand shifting & interconnection

If there are five cold, almost windless, winter days in 2050, then up to 15 GW of backup generation capacity will be required to ensure that electricity is always available.

In 2050, 53% of primary energy will be imported.
**Offshore Wind**

In 2007 the UK had around 0.4 GW of offshore wind capacity, and at the end of 2010, 1.3 GW. All of these were fixed to the seabed by solid foundations, with no floating offshore turbines yet present in the UK.

**Level 1**
Level 1 assumes that only the current turbines and those already advanced in the planning process are built. Offshore wind capacity initially rises from 1 GW to 8 GW in 2025 then reduces to zero by 2045 as decommissioned sites are not replanted. 8 GW is equivalent to around 1400-5.8 MW turbines (although in reality turbines would have different capacities) and generates around 29 TWh/y at 2025.

**Level 2**
Level 2 assumes that capacity increases to 60 GW by 2040 and is then maintained. This means building and maintaining about 10 000 of the 5.8-MW turbines in total. In this scenario the sea area occupied by wind farms is about 10 800 km², about half the area of Wales. It requires maintaining the same build rate that Germany achieved for onshore turbines from 2000 to 2010 over a 20-year period in the UK and in an offshore environment. 60 GW of offshore wind turbines generates around 237 TWh/y in 2050.

**Level 3**
Level 3 assumes that capacity rises to 45 GW by 2025, and to 100 GW by 2050, which is equivalent to around 17 000 5.8-MW turbines. The sustained installation rate is 5 GW per year. Installing 5 GW per year might require roughly 30 jack-up barges and means building offshore wind turbines at a rate never before achieved in any country. The sea area occupied by wind farms is 18 000 km², close to the area of Wales. The combined weight of steel and concrete in these turbines is roughly 0.4 tonnes for every Briton. 60 GW of offshore wind turbines generates around 395 TWh/y in 2050.

**Level 4**
Level 4 assumes that capacity rises to 68 GW by 2025, and to 236 GW by 2050—a 180-fold increase from 2010. The sustained installation rate required is 6 GW per year of fixed turbines (which requires roughly 30 jack-up barges) plus 6 GW/y of floating turbines. In total, this is equivalent to about 40 000 5.8-MW turbines being built by 2050. The costs of offshore wind installation and maintenance increase with the distance from shore and water depth. For level 4, the sea area occupied by wind farms is over 42 000 km², roughly twice the area of Wales, including both fixed and floating turbines. If 236 GW of the 5.8 MW turbines were arranged uniformly along 3400 km of coastline, there would be 12 of them per kilometre, generating around 929 TWh/y in 2050. The combined weight of steel and concrete in these turbines is 0.9 tonnes for every Briton.

**Figure 1.** UK offshore wind capacity versus time, historic (to 2010) and assumptions (from 2010 onwards), compared with onshore wind in Spain, Germany, EU, and world totals.
This pathway should meet the UK 2050 climate change target.

UK electricity demand
TWh/yr of electricity

UK electricity supply
TWh/yr of electricity

Greenhouse gas emissions from electricity
MtCO2e/yr

2050 emissions will be 80% below 1990 levels.
International aviation and shipping emissions are not included in the UK's 2050 target but are included here to enable emissions from all sectors to be considered.

Energy security
Storage, demand shifting & interconnection

If there are five cold, almost windless, winter days in 2050, then up to 15 GW of backup generation capacity will be required to ensure that electricity is always available.

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Conventional power stations are built automatically to fill any shortfall in electricity supply. Coal, Oil and Natural Gas are...
This pathway should meet the UK 2050 climate change target.

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2050 emissions will be 80% below 1990 levels. International aviation and shipping emissions are not included in the UK’s 2050 target but are included here to enable emissions from all sectors to be considered.
Illustration of the number of thermal power stations in 2050 (scales and positions are arbitrary).

- 114 x 215 kt/y waste to energy conversion facilities
- 100 x 0.01 GW geothermal stations
- 33 x 1.2 GW coal, gas or biomass power stations with CCS
- 25 x 1 GW gas standby power stations
- 13 x 3 GW nuclear power station
- 4 x 2 GW coal, gas or biomass power stations without CCS
This pathway should meet the UK 2050 climate change target.
| Nuclear Fission | 1000 W/m² |
A consultation exercise in full swing
How to get the UK off fossil fuels

- Transport, Heating, Electricity
  - Electrify all transport
  - Insulate all buildings; read all meters
  - Electrify all building-heating
    - air-source or ground-source heat pumps
    - (some combined-heat-and-power where low-carbon fuel available)

- Our renewables
- Nuclear? (stop-gap?)
- 'Clean coal'? (stop-gap)
- Other people's renewables
- Storage + interconnectors, to match supply to demand

- Research and innovation
- Public and political engagement
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Save or share this pathway
The 2050 Pathways Approach

For each demand sector, and each supply sector

- lay out the range of what's technically possible
  - or what might be technically possible

- four trajectories

Behaviour and demand projected; only current commercially proven technology

- level 1: No effort towards security of supply, energy saving, or climate change

Build rates would require structural change to markets. Significant behaviour change and efficiency measures adoption. Any technology that has been demonstrated in the laboratory.

- level 2: Effort likely to be viewed as achievable by most or all stakeholders

Very high levels of behaviour change. Any technology that is physically possible and might be developed + deployed before 2050. A level of build effort commensurate with that pursued during World War II, or the American efforts for a manned moon landing.

- level 3: Effort unlikely to happen without significant change from current systems

- level 4: Effort at the extreme upper end of the believable scale

Build a model of the energy system

- a calculator that computes the consequences of any set of choices ('pathway')

Explore which pathways meet goals of

- energy security
- carbon emissions reductions
UK energy demand
TWh/yr of final energy

2010-2050

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If there are five cold, almost windless, winter days in 2050, then up to 27 GW of backup generation capacity will be required to ensure that electricity is always available.

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Demand-side options - Transport

Have small frontal area per person
Have small weight per person
Go slowly
Go steadily
Convert energy efficiently
**UK energy demand**
TWh/yr of final energy

**UK energy supply**
TWh/yr of primary energy

**UK greenhouse gas emissions**
MtCO2e/yr

**Domestic transport behaviour**
1 2 3 4

**Domestic transport electrification**
1 2 3 4

**Domestic freight**
1 2 3 4

**International aviation**
1 2 3 4

**International shipping**
A B C D

**Average temperature of homes**
1 2 3 4

**Home insulation**
1 2 3 4

**Home heating electrification**
A B C D

**Home heating that isn’t electric**
A B C D

**Home lighting & appliances**
1 2 3 4

**Electrification of home cooking**
A B

**Growth in industry**
A B C

**Energy intensity of industry**
1 2 3

**Commercial demand for heating and cooling**
1 2 3

**Commercial heating electrification**
A B C D

**Commercial heating that isn’t electric**
A B C D

**Commercial lighting & appliances**
1 2 3 4

**Electrification of commercial cooking**
A B

**Nuclear power stations**
1 2 3 4

**CCS power stations**
1 2 3 4

**CCS power station fuel mix**
A B C D

**Offshore wind**
1 2 3 4

**Onshore wind**
1 2 3 4

**Tidal and wave**
1 2 3 4

**Biomass power stations**
1 2 3 4

**Solar panels for electricity**
1 2 3 4

**Solar panels for hot water**
1 2 3 4

**Geothermal electricity**
1 2 3 4

**Hydroelectric power stations**
1 2 3 4

**Small-scale wind**
1 2 3 4

**Electricity imports**
1 2 3 4

**Energy security**

**Storage, demand shifting & interconnection**
1 2 3 4

If there are five cold, almost windless, winter days in 2050, then up to 27 GW of backup generation capacity will be required to ensure that electricity is always available.

In 2050, 40% of primary energy will be imported.

**Geosequestration**
1 2 3 4

2050 emissions will be 72% below 1990 levels.

International aviation and shipping emissions are not included in the UK’s 2050 target but are included here to enable emissions from all sectors to be considered.

**Conventional power stations** are built automatically to fill any shortfall in electricity supply. Coal, Oil and Natural Gas are...
Demand-side options - heating

**Options for energy-saving:**

- Reduce **temperature difference**
  - Turn the thermostat down
- Reduce **leakiness**
- Increase **CoP** of heat-creation

**Equations:**

\[
\text{Heat loss} = \text{Leakiness} \times \text{Average temperature difference}
\]

\[
\text{Power required} = \frac{\text{Heat loss}}{\text{Coefficient of performance of heat-creation}}
\]
UK energy demand
TWh/yr of final energy

UK energy supply
TWh/yr of primary energy

UK greenhouse gas emissions
MtCO2e/yr

2050 emissions will be 72% below 1990 levels.

International aviation and shipping emissions are not included in the UK's 2050 target but are included here to enable emissions from all sectors to be considered.

Energy security
Storage, demand shifting & interconnection

If there are five cold, almost windless, winter days in 2050, then up to 27 GW of backup generation capacity will be required to ensure that electricity is always available.

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Geosequestration
1 2 3 4

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In 2050, 40% of primary energy will be imported.

Conventional power stations are built automatically to fill any shortfall in electricity supply. Coal, Oil and Natural Gas are available from multiple sources and can be quickly ramped up.
This pathway should meet the UK 2050 climate change target.

UK energy demand
TWh/yr of final energy

UK energy supply
TWh/yr of primary energy

UK greenhouse gas emissions
MtCO2e/yr

~13 3GW power stations delivering ~280 TWh/yr

Nuclear power stations
CCS power stations
CCS power station fuel mix

Offshore wind
Onshore wind
Tidal wave
Biomass power stations
Solar panels for electricity
Solar panels for hot water
Geothermal electricity
Hydroelectric power stations
Small-scale wind
Electricity imports

Geosequestration
2050 emissions will be 80% below 1990 levels.

International aviation and shipping emissions are not included in the UK’s 2050 target but are included here to enable emissions from all sectors to be considered.

Energy security
Storage, demand shifting & interconnection

If there are five cold, almost windless, winter days in 2050, then up to 15 GW of backup generation capacity will be required to ensure that electricity is always available.

In 2050, 53% of primary energy will be imported.
**Offshore Wind**

In 2007 the UK had around 0.4 GW of offshore wind capacity, and at the end of 2010, 1.3 GW. All of these were fixed to the seabed by solid foundations, with no floating offshore turbines yet present in the UK.

**Level 1**

Level 1 assumes that only the current turbines and those already advanced in the planning process are built. Offshore wind capacity initially rises from 1 GW to 8 GW in 2025 then reduces to zero by 2045 as decommissioned sites are not replanted. 8 GW is equivalent to around 1400-5.8 MW turbines (although in reality turbines would have different capacities) and generates around 29 TWh/y at 2025.

**Level 2**

Level 2 assumes that capacity increases to 60 GW by 2040 and is then maintained. This means building and maintaining about 10 000 of the 5.8-MW turbines in total. In this scenario the sea area occupied by wind farms is about 10 800 km², about half the area of Wales. It requires maintaining the same build rate that Germany achieved for onshore turbines from 2000 to 2010 over a 20-year period in the UK and in an offshore environment. 60 GW of offshore wind turbines generates around 237 TWh/y in 2050.

**Level 3**

Level 3 assumes that capacity rises to 45 GW by 2025, and to 100 GW by 2050, which is equivalent to around 17 000 5.8-MW turbines. The sustained installation rate is 5 GW per year. Installing 5 GW per year might require roughly 30 jack-up barges and means building offshore wind turbines at a rate never before achieved in any country. The sea area occupied by wind farms is 18 000 km², close to the area of Wales. The combined weight of steel and concrete in these turbines is roughly 0.4 tonnes for every Briton. 60 GW of offshore wind turbines generates around 395 TWh/y in 2050.

**Level 4**

Level 4 assumes that capacity rises to 68 GW by 2025, and to 236 GW by 2050 — a 180-fold increase from 2010. The sustained installation rate required is 6 GW per year of fixed turbines (which requires roughly 30 jack-up barges) plus 6 GW/y of floating turbines. In total, this is equivalent to about 40 000 5.8-MW turbines being built by 2050. The costs of offshore wind installation and maintenance increase with the distance from shore and water depth. For level 4, the sea area occupied by wind farms is over 42 000 km², roughly twice the area of Wales, including both fixed and floating turbines. If 236 GW of the 5.8 MW turbines were arranged uniformly along 3400 km of coastline, there would be 12 of them per kilometre, generating around 929 TWh/y in 2050. The combined weight of steel and concrete in these turbines is 0.9 tonnes for every Briton.
This pathway should meet the UK 2050 climate change target.

UK electricity demand
TWh/yr of electricity

UK electricity supply
TWh/yr of electricity

��house gas emissions from electricity
MtCO2e/yr

Domestic transport behaviour
Domestic transport electrification
Domestic freight
International aviation
International shipping

Average temperature of homes
Home insulation
Home heating electrification
Home heating that isn’t electric
Home lighting & appliances
Electrification of home cooking

Growth in industry
Energy intensity of industry
Commercial demand for heating and cooling
Commercial heating electrification
Commercial heating that isn’t electric
Commercial lighting & appliances
Electrification of commercial cooking

Nuclear power stations
CCS power stations
CCS power station fuel mix

Offshore wind
Onshore wind
Tidal and wave
Biomass power stations
Solar panels for electricity
Solar panels for hot water
Geothermal electricity
Hydroelectric power stations
Small-scale wind
Electricity imports

Land dedicated to bioenergy
Livestock and their management
Volume of waste and recycling
Marine algae
Type of fuels from biomass
Bioenergy imports

Geosequestration
2050 emissions will be 80% below 1990 levels.

International aviation and shipping emissions are not included in the UK’s 2050 target but are included here to enable emissions from all sectors to be considered.

Energy security
Storage, demand shifting & interconnection

If there are five cold, almost windless, winter days in 2050, then up to 15 GW of backup generation capacity will be required to ensure that electricity is always available.

In 2050, 53% of primary energy will be imported.
This pathway should meet the UK 2050 climate change target

2050 emissions will be 80% below 1990 levels.

International aviation and shipping emissions are not included in the UK’s 2050 target but are included here to enable emissions from all sectors to be considered.
This pathway should meet the UK 2050 climate change target

2050 emissions will be 80% below 1990 levels. International aviation and shipping emissions are not included in the UK's 2050 target but are included here to enable emissions from all sectors to be considered.
Land and sea use in 2050 (positions are arbitrary)

- Offshore wind
- Marine algae
- Tidal stream
- Tidal range
- Solar thermal
- Hydro
- Micro wind
- Solar PV
- Onshore wind
- Energy crops
- Forest

Illustration of the number of thermal power stations in 2050 (scales and positions are arbitrary)

- 114 x 215 kt/y waste to energy conversion facilities
- 100 x 0.01 GW geothermal stations
- 33 x 1.2 GW coal, gas or biomass power stations with CCS
- 25 x 1 GW gas standby power stations
- 13 x 3 GW nuclear power station
- 4 x 2 GW coal, gas or biomass power stations without CCS
This pathway should meet the UK 2050 climate change target.

Illustration of scale of land and sea use in 2050 (positions are arbitrary).

- Offshore wind
- Marine algae
- Solar thermal
- Hydro
- Micro wind
- Solar PV
- Onshore wind
- Energy crops
- Forest
- Biocrops
- Wave

Illustration of the potential uses of land and sea in 2050 (scale is arbitrary):
- 114 x 215 kt/y with wave power
- 15 x 500 MW with wave power

Example pathways:

Reference
- Maximum demand, no supply
- Maximum supply, no demand

1. Spread effort
2. Low energy demand: all
3. Low energy demand: individuals
4. Low energy demand: businesses
5. Electrify all possible sectors
6. Electrify all except heat
7. Electrify all except transport
8. Solid biofuel focus
9. Liquid biofuel focus
10. Gas biofuel focus
11. Renewable generation
12. Offshore renewable generation
13. Nuclear generation
14. CCS generation
15. Gas generation
16. Microgeneration
17. Hedging strategy

Friends of the Earth
Campaign for Protection of Rural England
Prof Nick Jenkins
Mark Brinkley
National Grid
Energy Technologies Institute
Atkins
Mark Lynas
What we need for most 2050 pathways

- Backup plans
  - eg, in case low-cost electric vehicles don't materialise
    - hydrogen
  - or in case climate sensitivity turns out bigger than expected
    - geoengineering research
Novel heat pumps

Isentropic
Novel storage technologies

Isentropic

30 GWh Equivalent Capacity

Isentropic's storage schematic 2MW, 16MWh pumped heat electrical storage
Energy storage in underwater wind bags?

Seamus Garvey
Novel wind turbines

Seamus Garvey
Innovation needs (top 6) for the UK

- **Efficiency**
  - building insulation
  - vehicles (electric and hydrogen?)

- **Wind**

- **Heat pumps**

- **Biomass- and waste-to-good-things**

- **Carbon Capture and Storage**

- **Energy Storage**
  - electricity storage
  - interconnectors; smart demand-management
  - seasonal heat stores
2008, USA

Nuclear heat: 22.5 kWh/d
Oil for electricity: 1.3 kWh/d
Natural gas for electricity: 19 kWh/d
Coal: 61 kWh/d

Wind: 0.5 kWh/d
Solar electricity: 0.008 kWh/d
Hydro: 2.3 kWh/d

Geothermal: 0.9 kWh/d
Biomass: 10 kWh/d

More Oil: 105 kWh/d
More Natural gas: 44 kWh/d
Non-electrical energy use – chemical energy and heat

inputs to electricity power stations
Delivered electricity (37 kWh/d total)

Total Electricity consumption is 37 kWh/d/p - of which coal delivers 18 kWh/d/p

2050?

Wind: 42 kWh/d
Nuclear: 42 kWh/d
Biomass: 42 kWh/d
Solar in deserts: 42 kWh/d
2100 GW of wind (60-fold increase)
525 one-gigawatt nuclear power stations (five-fold increase)
Personalized

One 2-MW turbine for every 300 people

7 nukes for LA
5 nukes for Chicago
4 nukes for Houston
2 nukes for San Diego
1 nuke for Denver CO
1 nuke for Boston MA
1 nuke for Las Vegas NV
1 nuke for Portland OR...

4000 sq m per person

30 eSolar mirrors per person; & one tower for every 400 people
Innovation needs (additional) for the world

- Solar power
- Deep geothermal
- Proliferation-resistant, safe, low-waste nuclear power
Getting off fossil fuels is not easy, but it is possible

A Plan that adds up must have some or all of:
- country-sized renewable facilities
- renewables from other people's countries
- lots of nuclear power and 'clean coal'

And efficiency too of course

'Okay - it's agreed; we announce - "to do nothing is not an option!" then we wait and see how things pan out...'

Lowe, Private Eye
GHG emissions, year 2000

Data source: Climate Analysis Indicators Tool (CAIT) Version 4.0. (Washington, DC: World Resources Institute, 2007).
GHG emissions, year 2000

Data source: Climate Analysis Indicators Tool (CAIT) Version 4.0. (Washington, DC: World Resources Institute, 2007).
GHG emissions versus energy use

Energy use (kWh/d per person)

GHG emissions (tCO₂/y per person)

Deployment curves

Updated after data produced by Prof. Dennis Loveday. “Market penetration of energy-efficiency related measures” (2003)
30 mirrors per person, and one tower for every 400 people
Solar power

Power per unit area in Britain
Solar electric (photovoltaics)
Sustainable Energy – without the hot air

David JC MacKay

Publisher: UIT Cambridge

www.withouthotair.com