Sustainable Energy
- without the hot air

David MacKay
Department of Physics
University of Cambridge

www.withouthotair.com
Summary: We need a plan that adds up

- We need to get off fossil fuels
  - Numbers, not adjectives
  - Not easy; but possible

- All renewables are diffuse
  - To make a difference, renewable facilities have to be country-sized

- The supply options are:
  - Our renewables
  - Other countries' renewables
  - Nuclear

www.withouthotair.com
We need to get off fossil fuels

1: fossil fuels will run out
   + maybe future generations would prefer to do something smarter with them

2: climate change

3: security of supply
'Security of supply'

Magnus platform - delivers 5GW; 71,000 tonnes of steel

Photo by Terry Cavner
Something must be done!
Total GHG emissions (2000) = 34 GtCO$_2$(e)

Data source: Climate Analysis Indicators Tool (CAIT)
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Total GHG emissions (2000) = 34 GtCO$_2$\textsuperscript{(e)}

Data source: Climate Analysis Indicators Tool (CAIT)
Cumulative emissions (average for 1880–2004) – CO₂ only

1880-2004
Something must be done!
Make a world of difference
Neutralise your CO2 emissions now

We all contribute to CO2 emissions when we drive. We can all do something about it. It’s simple and doesn’t cost the earth. On average, it’s just £20 a year.

Neutralise your CO2 emissions now

Discover more about targetneutral

Reducing CO2 emissions one car at a time
'Do your bit' - Green tariffs

Let the power of nature into your home

Switch your energy to Powergen’s Go Green tariff and do your bit for the environment

Click here ➤
'Sustainable'

Generating a sustainable future

Positive Energy

2% of Powergen's electricity is from renewables
Efficiency through technology

'a highly fuel-efficient aircraft'

- it burns 12 percent less fuel per passenger-km than a 747
'Brown Takes Ride on Green Train'

"And the funniest thing is - it's only 20% biodiesel!"

A pump full of B5
Clean Urban Transport for Europe

hydrogen made from fossil fuels:

overall primary energy consumption by the hydrogen buses was between 80% and 200% greater than that of the baseline diesel bus.

GHG emissions were between 40% and 140% greater.
'Industry have done their bit'

The car industry has done its bit by making greener vehicles. Now we have to buy them, says Sean O'Grady

34 mpg
- 219g/km

The 2.4 Diesel is efficient and probably the best all-round choice, offering 34 mpg overall. During the past few years, it has...
Carbon emissions from cars

Polo (102 g/km)

Number of cars for sale

- Toyota Prius (104 g/km)
- Honda Civic 1.4 (109 g/km)
- Audi A3 (143 g/km)
- Jeep Cherokee 2.8 (246 g/km)
- Honda NSX 3.2 (291 g/km)
- Audi A8 (338 g/km)
- Jeep Commander 5.7 V8 (368 g/km)
- Toyota Land Cruiser Amazon 4.7 (387 g/km)
- Ferrari F430 (420 g/km)
- Ferrari Superamerica (499 g/km)

emissions (g CO2 per km)

top speed (km/h)

engine power (kW)
Something must be done!

Two reasons to join GREENPEACE
“If we’re going to cut greenhouse gases by 60% by 2050 there is no other possible way of doing that except through renewables”.

Michael Meacher

“Anybody who is relying upon renewables to fill the energy gap is living in an utter dream world and is, in my view, an enemy of the people.”

Sir Bernard Ingham

“We have a huge amount of wave and wind’.

‘Nuclear is a money pit’.

Ann Leslie

We need numbers, not adjectives
A rough guide to sustainable energy

- No millions, billions, or trillions
- Make quantities comprehensible and comparable

- Do calculations per person, to one significant figure

- Energy unit: kWh
- Power unit: kWh per day
- Fluxes: W per square metre
- Population density: square metres per person

Examples:
- 20 mins of kettle - 1 kWh
- Food - 3 kWh / day (*)
- Bath - 5 kWh (*)
- Litre of petrol - 10 kWh
- Aluminium can - 0.6 kWh

UK: 4000 m² per person
Drive a car 100km...

80 kWh

The 2.4 Diesel is efficient and probably the best all-round choice, offering 34mpg overall. During the past few years, it has even more space inside. The trouble is, the R-Class is furiously expensive, with prices starting at more than £38,000.
Average Power consumption, UK: 125 kWh/d each

125 kWh/day (Europe)
300 kWh/day (USA)

(Not including embodied energy in imports nor solar energy used by agriculture)

For CO₂ pollution, divide by 10:
100 kWh/day ≈ 10 tonnes CO₂/year

www.dti.gov.uk
Winds speeds Cambridge 2006 (m/s) Half-hourly and daily
$v = 6 \text{ m/s (force 4)}$

Wind farm 2 W/m$^2$ flat ground

**UK: 4000 m$^2$ per person**

Put wind farms on 10% of the country

- 400 square metres each

...Twice as much windpower as the whole world;
50 x Denmark's
7 x Germany's
# Renewables are diffuse

**Power per unit land area**

<table>
<thead>
<tr>
<th>Resource</th>
<th>Power per Area</th>
<th>Source</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>2 W/m²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Offshore wind</td>
<td>3 W/m²</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>3 W/m²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tidal stream</td>
<td>6 W/m²</td>
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</tr>
<tr>
<td>Solar PV panels</td>
<td>5 W/m²</td>
<td></td>
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</tr>
<tr>
<td>Plants</td>
<td>0.5 W/m²</td>
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<tr>
<td>Solar chimney (Spain)</td>
<td>0.1 W/m²</td>
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<tr>
<td>Concentrating solar power (desert)</td>
<td>15 W/m²</td>
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<tr>
<td>Ocean thermal</td>
<td>5 W/m²</td>
<td></td>
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<tr>
<td>Rain-water (Scotland)</td>
<td>0.24 W/m²</td>
<td></td>
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</tr>
<tr>
<td>Rain-water (England)</td>
<td>0.02 W/m²</td>
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</table>

To make a difference, renewable facilities have to be country-sized.
## Power per Unit Land Area

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To make a difference, renewable facilities have to be country-sized.
Bavaria Solar Park: $5 \text{ W/m}^2$; this picture shows $0.7 \text{ MW}$ (average)
All renewables are diffuse

Power per unit land area

Wind
Offshore wind
Tidal pools
Tidal stream
Solar PV panels
Plants
Solar chimney (Spain)
Concentrating solar power (desert)
Ocean thermal
Rain-water (Scotland) 0.24 W/m²
Rain-water (England) 0.02 W/m²

To make a difference, renewable facilities have to be country-sized.
Renewables are diffuse

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To make a difference, renewable facilities have to be country-sized
No green light for Severn barrage

Last modified: 01 October 2007

Europe’s most dynamic estuary will be destroyed by the construction of a barrage across the Severn while other less striking measures would cost less and could do more to cut carbon emissions.
Nuclear
Fission  1000 W/m²
We can't live on our own renewables - at least, not as we currently live.

<table>
<thead>
<tr>
<th>Energy Type</th>
<th>Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current consumption:</td>
<td>125 kWh/d per person</td>
</tr>
<tr>
<td>Geothermal:</td>
<td>2 kWh/d</td>
</tr>
<tr>
<td>Tide:</td>
<td>14 kWh/d</td>
</tr>
<tr>
<td>Wave:</td>
<td>1.6 kWh/d</td>
</tr>
<tr>
<td>Shallow offshore wind:</td>
<td>16 kWh/d</td>
</tr>
<tr>
<td>Hydro:</td>
<td>2 kWh/d</td>
</tr>
<tr>
<td>Biomass: food, biofuel, wood, landfill gas:</td>
<td>24 kWh/d</td>
</tr>
<tr>
<td>PV, 12 m²:</td>
<td>5 kWh/d</td>
</tr>
<tr>
<td>Solar heating (12 m²):</td>
<td>12 kWh/d</td>
</tr>
<tr>
<td>Wind:</td>
<td>20 kWh/d</td>
</tr>
</tbody>
</table>

www.withouthotair.com
The role of nuclear power in a low carbon economy

Paper 2: Reducing CO\textsubscript{2} emissions - nuclear and the alternatives

An evidence-based report by the Sustainable Development Commission

March 2006

<table>
<thead>
<tr>
<th>Source</th>
<th>Potential (Twh/yr)</th>
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<tbody>
<tr>
<td>Wave</td>
<td>2.3</td>
</tr>
<tr>
<td>Geothermal</td>
<td>10</td>
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<tr>
<td>Tide</td>
<td>2.4</td>
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<tr>
<td>Energy crops</td>
<td>9</td>
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<tr>
<td>Solar PV</td>
<td>12</td>
</tr>
<tr>
<td>Offshore</td>
<td>6.4</td>
</tr>
<tr>
<td>Wind</td>
<td>2</td>
</tr>
</tbody>
</table>

\*IEE's 'technical potential' is 'an upper limit that is unlikely ever to be exceeded even with quite dramatic changes in the structure of our society and economy'.
A consultation exercise in full swing
Save Our Scenery - Protecting Our Heritage Coastline

BEFORE

FROM LLANDUDNO PROMENADE

AFTER

FROM COLWYN BAY PROMENADE

saveourscenery.com
What Do We Stand For And What Not?

1) An area of scientific and natural interest. An area of natural beauty within which there is a nature reserve. Our environment and that of natural flora and fauna. An area for migrating birds. The conservation area of the village of Graveney. To protect the villages around (especially Graveney) from damage, destruction and industrialisation.

2) We oppose the planning applications of London Array Ltd also called Array and seek to protect the areas mentioned above from damage and destruction by the intended developments of London Array.

3) The planning applicants hope to obtain from Crown Estates a lease to develop a wind farm in the World in the Thames Estuary, the largest in the U.K. They hope to buy land at Cleve Hill, Graveney in order to construct their own large electrical sub-station in order to connect wind farm electricity to the National Grid, thus destroying parts of the land described in paragraph 1 above.
News

Giant Wind Farm Off English Coast Pits Town Against Shell, E.ON

Graveney was the site of the last combat on English soil when British forces battled a downed German bomber crew in 1940. Now the village is fighting a new enemy: the world’s biggest wind farm. The local council, acting on behalf of the town’s 473 residents, refused to permit a substation for the $1.5 billion London Array, which would put 271 wind turbines in the estuary of the River Thames. Royal Dutch Shell Plc and E.ON AG plan to bring power cables ashore near Graveney. “They say this is the only place they could put it — that’s rubbish,” said retiree George Schneider, 73, strolling on Saxon Shore Way, a rambling route across the coastal plain. “Why use a green-field site when there are other places?”

Job creation

In Porthcawl in south Wales, a pressure group called SOS Porthcawl has been set up to oppose plans for a wind farm four miles out to sea.

The proposal is for 30 turbines on Scarweather Sands, each 453 feet high.

It could provide enough energy for more than 40,000 homes.

The production of the turbines could also create 130 jobs - they are made in Wales at Bangor and more could be produced at Port Talbot.

Tourism

But SOS Porthcawl says the turbines will be noisy and visible from beauty spots, which would deter tourists.

Wind farm ‘a threat to our airport’

Southend Airport has raised serious objections to plans to build a new wind farm - even though the turbines would be nearly 15 miles to the north. Experts say a wind farm next to the defunct nuclear power station, at Billericay, air traffic control issues and might even interfere with radar. Airport managing director Alistair Welch raised the concerns at a public inquiry which is being held.

June 22, 2007 in Echo

Southend Airport has raised serious objections to plans to build a new wind farm - even though the turbines would be nearly 15 miles to the north.
Local people opposing plans to build one of the UK's biggest offshore wind farms on the south Wales coast met on Friday. Residents in Porthcawl will be shown plans of how the wind farm will look and highlight their opposition to the proposed 30-turbine installation at Rhossili Sands.

SOS Porthcawl was set up by campaigners in the town who say the wind farm will adversely affect the holiday resort which attracts surfers and tourists from all over the UK. The demonstration coincides with a public consultation into the project by developers United Utilities Green Energy.

Four-times British surf champion, Simon Tucker said there was a lot of feeling against the proposals within the town. "This demonstration is to ask the developers not to destroy the very environment they claim they are trying to protect," he said. Mr Tucker said the turbines, which are taller than the Statue of Liberty in New York, will destroy the panorama views and also have an impact on the sea.

"The turbines will change the shape of the sandbanks and the waves," he said. "If the waves are changed and people can no longer surf the sport because of the turbines then the town is going to die. The company behind the £100m scheme say the turbines, which are 120m above sea level, will generate enough power for 86,000 homes.

The site, which is to the west of Porthcawl, is approximately five miles off the coast.

Hundreds of fishermen gathered in the Wash to protest against plans to build offshore wind turbines.

The men from Boston, Skegness and King's Lynn are unhappy at government proposals to erect 250 wind turbines in the Greater Wash.

If it goes ahead, the facility would be part of one of the largest wind farms in the world.

Planning permission has already been granted for 60 turbines on two sites off the south Lincolnshire coast.

Project 'impractical' by BBC News

Andy Roper, who organised the protest, emphasised the fishermen's livelihoods are being threatened.
Winds of change will mean giant sea turbines

By Anthony Browne, Environment Editor

DOZENS of wind farms, each with hundreds of turbines up to 500ft high, are to be given the go-ahead off the coast between Scotland and Wales, around the Wash in East Anglia and in the Thames Estuary.

Yesterday's announcement was welcomed by some environmental groups; others have given warning that it will ruin views and damage sea life. Fishermen have said that they will be forced out of business.

Brian Wilson, the Energy Minister, said: "In theory, these areas could source enough electricity to power the whole of Britain, albeit intermittently. There is no doubt

Wind power 'a security risk

02 November 2007 08:15

Defence chiefs threw the future of East Anglia's wind energy industry into confusion last night after claiming that wind turbines could be a threat to national security.

Experts say the MoD now objects to about 50pc of applications to build onshore wind turbines because of concerns they affect the performance of military radar.
after the great British consultation exercise...

This would be a 15-fold increase of renewables
Today's supply of renewables

- Offshore wind: 0.03
- Small hydro: 0.022
- Large hydro: 0.19
- Biodiesel: 0.13
- Biomass (wood in homes): 0.07
- Biomass (cofiring): 0.12
- Biomass (landfill gas, sewage, waste incineration): 0.3
- Solar HW: 0.014
- Solar PV: 0.0003
- Wind: 0.16

All renewables in 2006: 1.05 kWh/d

Nuclear (2006): 3.4 kWh/d
How to get the UK off fossil fuels

- We need a plan that adds up!

- Transport, Heating, Electricity
  - Electrify all transport
  - Insulate all buildings
  - Electrify all building-heating
    - air-source or ground-source heat pumps
    - (not combined heat and power)

- Our renewables
- Nuclear? (stop-gap?)
- 'Clean coal'? (stop-gap)
- Other people's renewables
23,000 m² per person

1000 m² per person

Population
Population densities in Europe
International renewables

Each blob: 1500 sq km; 44km diameter; 10 GW if 30% solar farm, at 20 W/sq m.

65 blobs: $-16 \text{ kWh/d/p} \times 1\text{ Gp}$
Each blob: 1500 sq km; 44 km diameter;
10 GW if 30% solar farm, at 20 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
Andasol, Spain

10 W/m²
HVDC transmission

Photos and diagrams: ABB 2GW -->

3.1GW, 1360km

1.9GW, 1420km

0.7GW, 580km
Finland - Estonia: One pair of cables transmit 350 MW
Summary: We need a plan that adds up

- We need to get off fossil fuels
  - Numbers, not adjectives
  - Not easy; but possible

- All renewables are diffuse
  - to make a difference, renewable facilities have to be country-sized

- The supply options are:
  - our renewables
  - other countries' renewables
  - nuclear

www.withouthotair.com
Jevons' paradox

"as technological improvements increase the efficiency with which a resource is used, total consumption of that resource may increase, rather than decrease."

For example, from 1900 to 2000, passenger transportation in the USA became 5 times more energy-efficient; but nowadays, the average person travels 50 times further.
Heat loss = Leakiness × Average temperature difference
(kWh/d)  (kWh/d/°C)  (°C)
Turn the thermostat down

Heat loss = Leakiness × Average temperature difference
(kWh/d)  (kWh/d/°C)  (°C)

91 degree-days of cooling
3188 degree-days of heating
2265 degree-days of heating
1748 degree-days of heating

Leakiness: 8 kWh/d/°C

Average temperature difference

Temperature demand, in degree-days per year
Reduce leakiness

New leakiness: 6 kWh/d/°C
Read your meters!

**Gas**

![Gas Usage Chart]

**Electricity**

![Electricity Usage Chart]
Read your meters!

**Gas**
- Condensing boiler installed
- Lower thermostat
- More insulation
- More glazing

**Electricity**
Combined heat and power?

'Microgeneration', 'Decentralization'
Can we do better than Combined Heat and Power? (bearing in mind we want to heat buildings)

- Heat pumps
FTXS25E

A Daikin Split System will air condition one room or an area of your home. Discreet wall-mounted models, compact floor consoles and versatile floor and ceiling units are all part of the Daikin range.

Create perfect conditions all year round with Daikin reverse cycle split system air conditioners.

<table>
<thead>
<tr>
<th>Overview</th>
<th>Features</th>
<th>Specifications</th>
<th>Controllers</th>
<th>Downloads</th>
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<tr>
<td><strong>Unit</strong></td>
<td>Indoor Unit</td>
<td>FTXS25EVMA</td>
<td>RXS25EAVMA</td>
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<td>Outdoor Unit</td>
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<td><strong>Rated Capacity</strong></td>
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<td>Heat (kW)</td>
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<td>Cool (kW)</td>
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<td>Heat (kW)</td>
<td>1.2-4.5</td>
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<td>5 steps, quiet and automatic</td>
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<td><strong>Power Input (min-rated-max)</strong></td>
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<td>0.30-0.60-0.80</td>
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<tr>
<td></td>
<td>Heat (kW)</td>
<td>0.29-0.83-1.34</td>
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<tr>
<td><strong>C.O.P</strong></td>
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<td>4.17/4.10</td>
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<tr>
<td><strong>Power Supply</strong></td>
<td>1 phase, 220-240V, 50Hz</td>
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</tbody>
</table>
Can we do better than Combined Heat and Power?

- Heat pumps

ground-source or air-source
Wind fluctuates

Even when added over a whole country

Total output (in MW) of all windfarms in Eire, April 2006 - April 2007

www.eirgrid.com
'Wind is intermittent, so requires fossil-fuel back-up'
Figure 26.2. Total output, in MW, of all windfarms of the Republic of Ireland, from April 2006 to April 2007 (top), and detail from January 2007 to April 2007 (middle), and February 2007 (bottom). Peak electricity demand in Ireland is about 5000 MW. Its wind ‘capacity’ in 2007 is 745 MW, dispersed in about 60 wind farms. Data are provided every 15 minutes by www.eirgrid.com.

Scale this up: with 33 GW of capacity, expect slew rate of 3.7 GW per hour - an unprecedented problem for Britain?

Every morning, demand rises at a slew rate of 6.5 GW per hour.
Dinorwig is the home of a 9 GWh storage system, using Marchlyn Mawr (615E,620N) and Llyn Peris (590E,598N) as its upper and lower reservoirs.

Loch Sloy illustrates the sort of location where a 40 GWh storage system could be created.

or smart storage ('net-energy')
Pumped storage

Kannagawa Power Plant (29 GWh)
www.ieahydro.org

Okinawa Seawater Pumped Storage Power Plant (0.2 GWh)
www.ieahydro.org
Output - 30 MW
Huge expansion for wind turbines

There could be more than two offshore wind turbines per mile of UK coastline under plans being set out by ministers.

Business Secretary John Hutton says he wants to open up British seas to allow enough new turbines - up to 7,000 - to power all UK homes by the year 2020.

John Sauven, the executive director of Greenpeace, said that the plans amounted to a "wind energy revolution". "And Labour needs to drop its obsession with nuclear power, which could only ever reduce emissions by about 4% at some time in the distant future."

How does nuclear's pathetic 4% compare with the proposed offshore wind?

'33GW' of offshore wind would deliver on average 10GW, which is 4kWh/d per person.
Nuclear Fission ('sustainable' = 1000 years)

Uranium

- Once-through: 0.1 kWh/d
- Fast breeder: 5 kWh/d
- Ocean Uranium: 7 kWh/d
- River Uranium: 0.08 kWh/d

Thorium

- Conventional reactor: 4 kWh/d
- ‘Energy amplifier’: 60 kWh/d
- Mined Thorium: 420 kWh/d
Doable?

- DT reaction
  - requires Lithium and Deuterium
- DD reaction
  - requires Deuterium

Lithium fusion: 110 kWh/d
DD reaction

D lasts ~ 1 billion years
**Summary**

- People say things that don't add up
  - Planes, Volvos, Green tariff, Offsetting
  - Nuclear versus wind

- We need numbers not adjectives

- Renewables are diffuse
  - To make a difference, renewable power facilities need to be country-sized
  - Britain can't live on its own renewables

- How to get off fossil fuels
  - Electrify all transport
  - Electrify all building-heating using heat pumps
  - Renewables
  - Nuclear power
  - (Clean coal)
  - Solar power in someone else's desert
# Carbon translation chart

<table>
<thead>
<tr>
<th>kWh/d each</th>
<th>kWh(e)/d each</th>
<th>t CO₂/y each</th>
<th>Mt CO₂/y / UK</th>
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UK (1990) 17
UK (2005) 16

World (2005)
90% target 7
90% target 6

'Safe and fair'
2
'Safe'
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<th>TWh/y / UK</th>
<th>Mtoe/y / UK</th>
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1 kWh/d the same as 1/24 kW

GW often used for ‘capacity’ (peak output)

TWh/y often used for average output

1 Mtoe ‘one million tonnes of oil equivalent’

‘UK’ = 60 million people

USA: 300 kWh/d each

Europe: 120 kWh/d each

UK Electricity fuel input (2004)

UK Electricity (2004)

UK Nuclear (2004)
Nuclear power 'completely infeasible'?

"For nuclear power to make a significant contribution to a reduction in global carbon emissions in the next two generations, the industry would have to construct nearly 3000 new reactors [over 60 years]...

[This is] a pipe dream and completely infeasible. The highest historic rate of build is 3.4 new reactors a year."

(Guardian, citing an Oxford Research Group report, 4th July 2007)