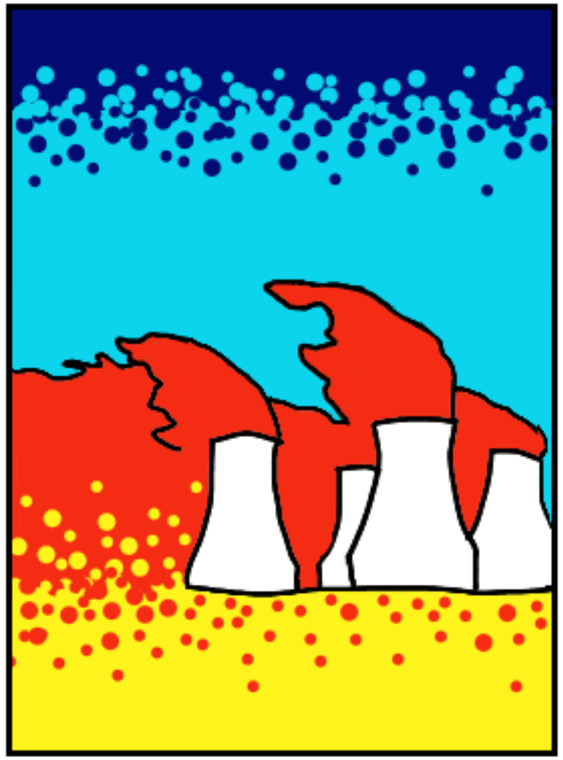
Sustainable Energy

- what actions really make a difference?

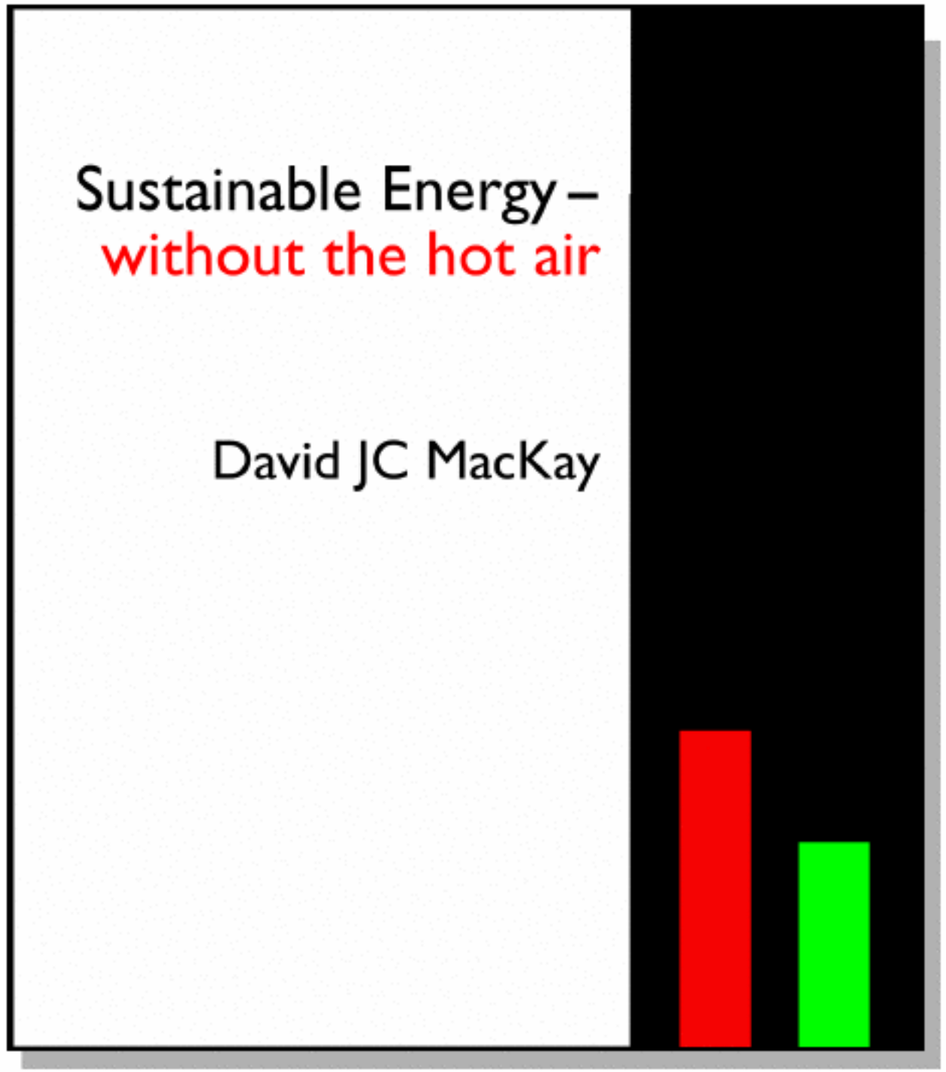


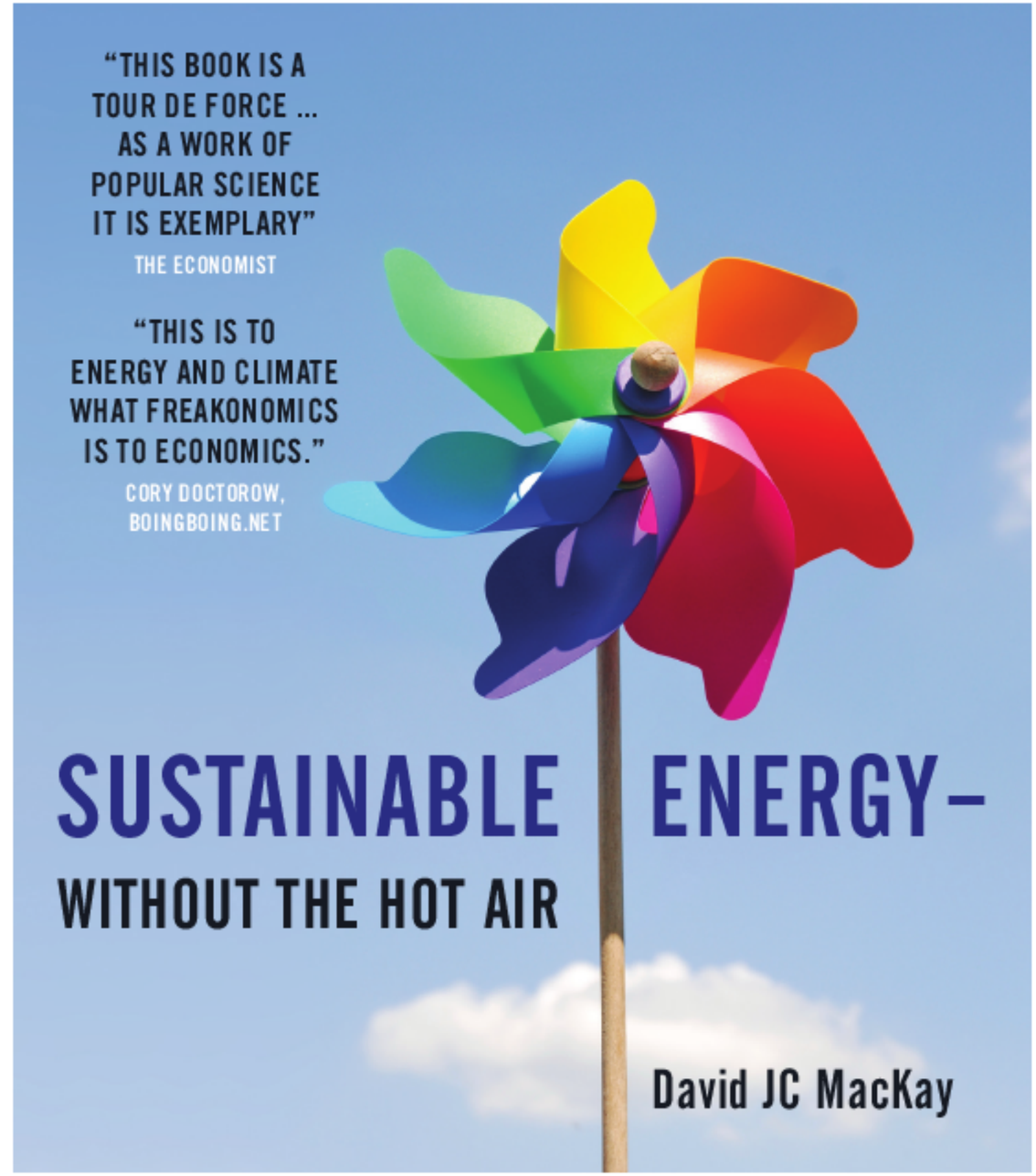
David MacKay FRS

Cavendish Laboratory, University of Cambridge

Department of Energy and Climate Change

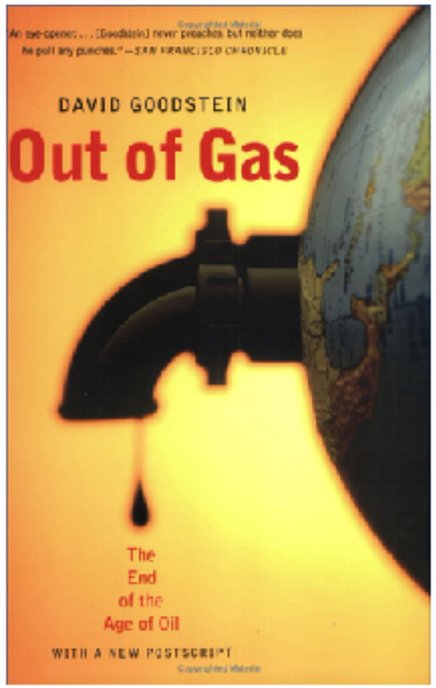
www.withouthotair.com





www.withouthotair.com

We have an addiction to fossil fuels, and it's not sustainable



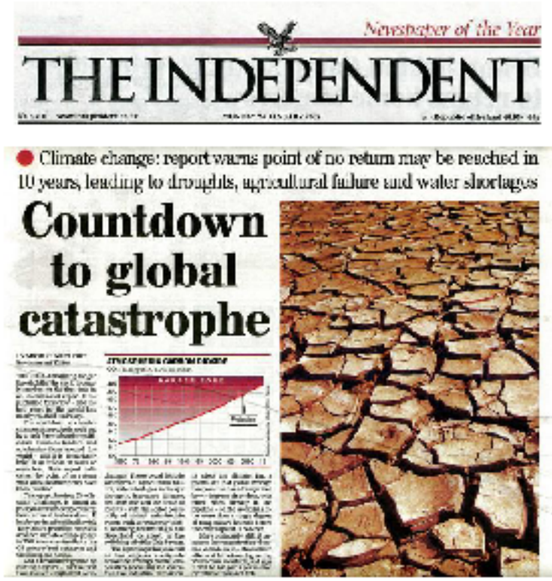


Photo by Terry Cavner

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: kWh per day

- Power per unit area: W per square metre

- Population density: square metres per person

  UK: $4000\ \mathrm{m}^2$ 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

Drive a car 100km...

80 kWh

ything.

HEAD
huge prob-
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space and
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arque
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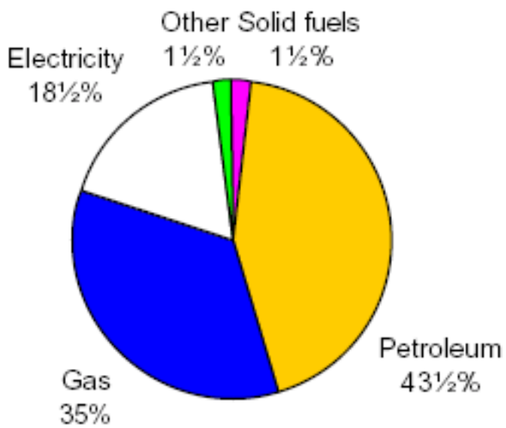
he should

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

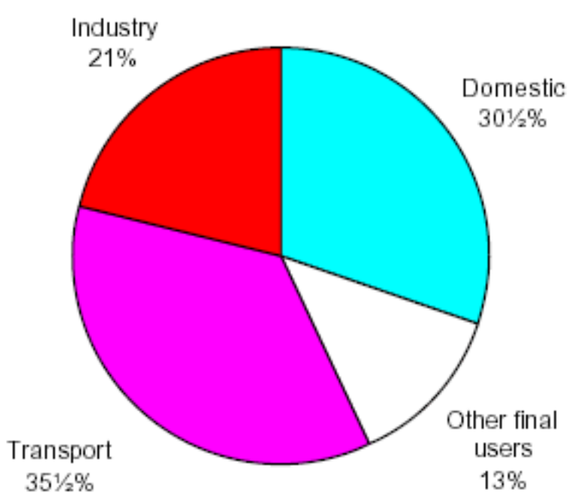
trouble is, the R-Class is furiously expensive, with prices starting at more than £38,000.

Practically perfect: the Volvo XC90

Average power consumption, UK: 125 kWh/d/p



2004



www.dti.gov.uk

125 kWh/day (Europe)

250 kWh/day (USA)

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

For CO_2 pollution, divide by 10:

100 kWh/day $\simeq$ 10 tonnes CO_2/y

Wind

Current consumption

Current consumption: 125 kWh/d per person

$v = 6\,\mathrm{m/s}$ (force 4)	
Wind farm	$2\,\mathrm{W/m^2}$ flat ground

UK: $4000\ \mathrm{m}^2$ per person

Put wind farms on 10% of the UK

- 400 square metres each

Wind: 20 kWh/d

...Twice as much windpower as the whole world;

50 x Denmark's

7 x Germany's

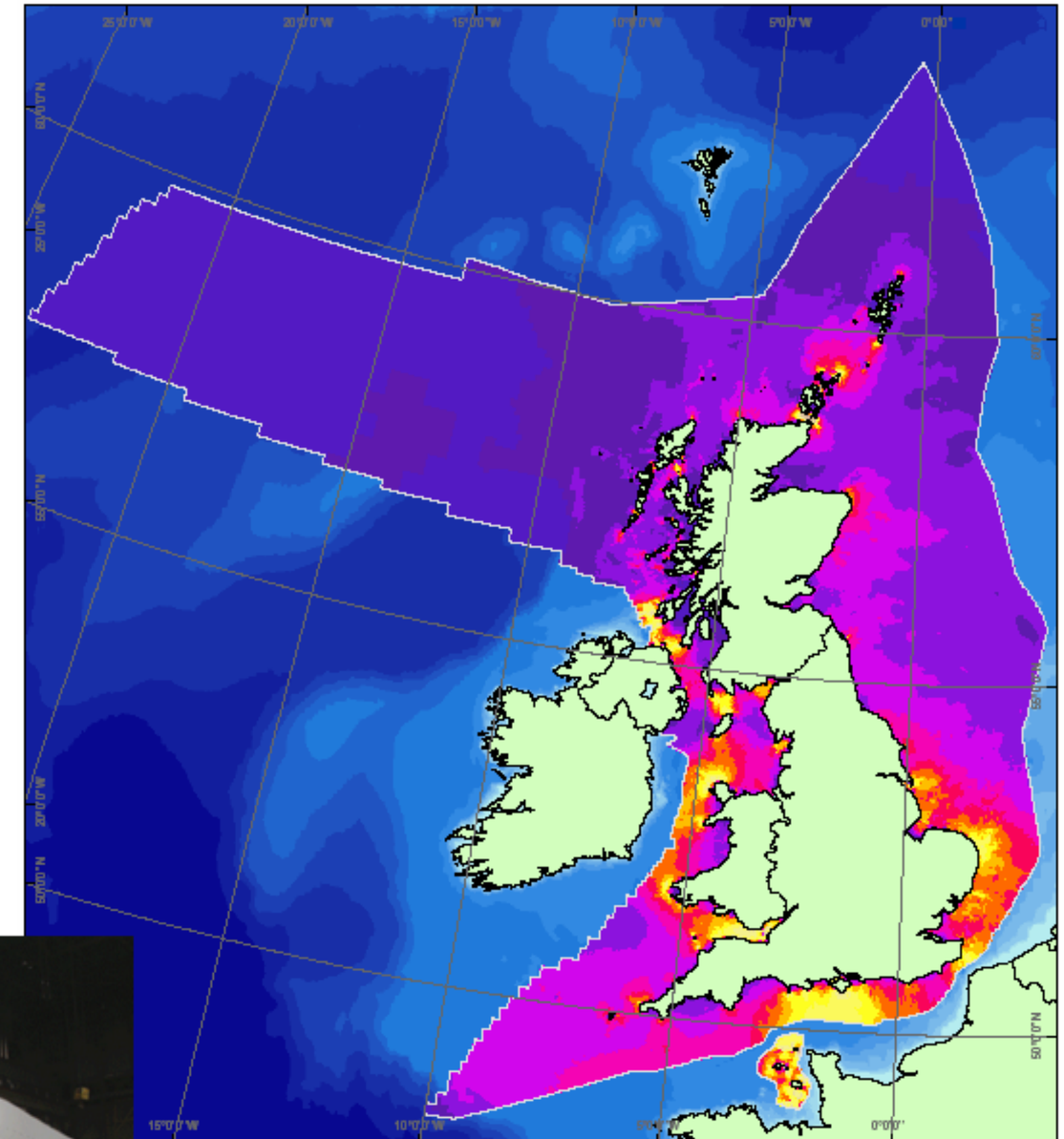
One 2-MW turbine for every 500 people

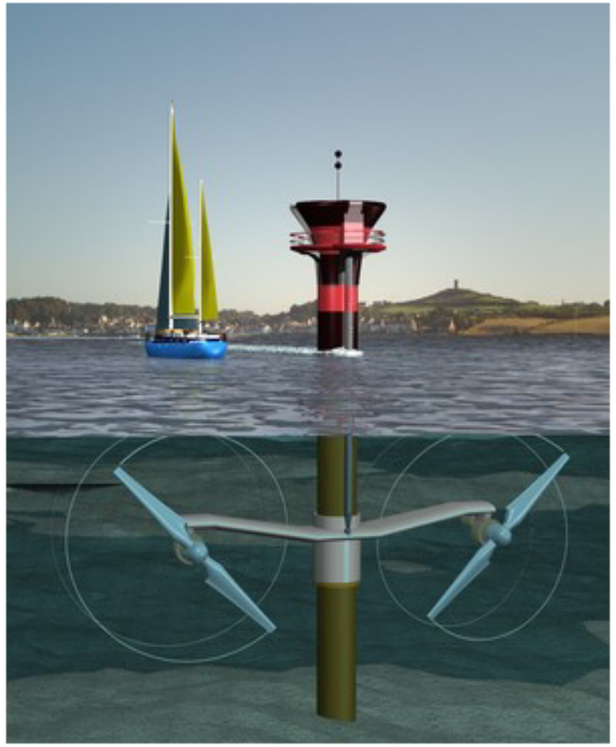
Roughly 100-fold increase over today's UK wind

Renewables are diffuse

Power per unit land area	
Wind	$2\,\mathrm{W/m^2}$
Offshore wind	$3\,\mathrm{W/m^2}$
Tidal pools	$3\,\mathrm{W/m^2}$
Tidal stream	$8\,\mathrm{W/m^2}$
Solar PV panels	$5\text{–}20\,\mathrm{W/m^2}$
Plants	$0.5\,\mathrm{W/m^2}$
Solar chimney (Spain)	$0.1\,\mathrm{W/m^2}$
Concentrating solar power (desert)	$15\text{–}20\,\mathrm{W/m^2}$
Ocean thermal	$5\,\mathrm{W/m^2}$
Rain-water (highlands)	$0.24\,\mathrm{W/m^2}$
Rain-water (lowlands)	$0.02\,\mathrm{W/m^2}$

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





marineturbines.com

marineturbines.com

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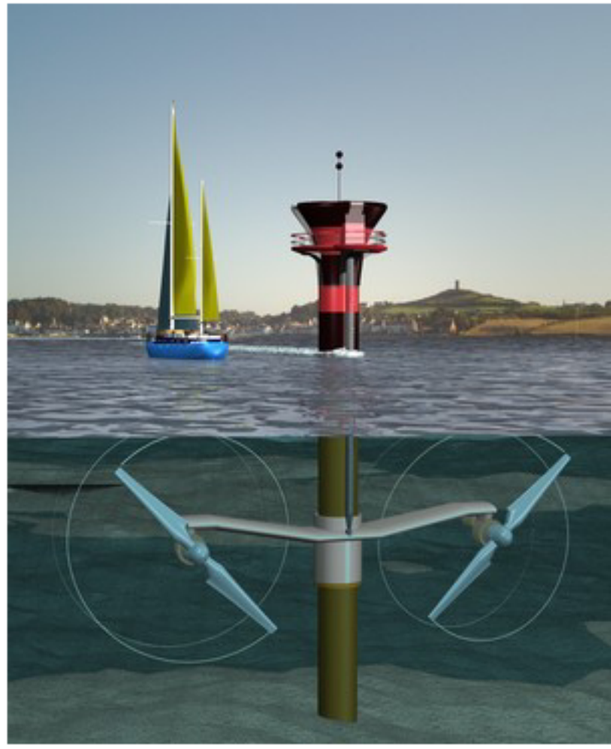

marineturbines.com

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

Bavaria Solar Park: $5\,\mathrm{W/m^2}$; this picture shows $0.7\,\mathrm{MW}$ (average)

All renewables are diffuse

Power per unit land area	
Wind	2 W/m
Offshore wind	3 W/m
Tidal pools	3 W/m
Tidal stream	8 W/m
Solar PV panels	5–20 W/m
Plants	0.5 W/m
Solar chimney (Spain)	0.1 W/m
Concentrating solar power (desert)	15–20 W/m
Ocean thermal	5 W/m^2
Rain-water (highlands)	0.24 W/m^2
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- To make a difference, renewable facilities have to be country-sized

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http://www.auchencorth.org.uk/

Go

Penicuik Environment Protection Association

PEPA

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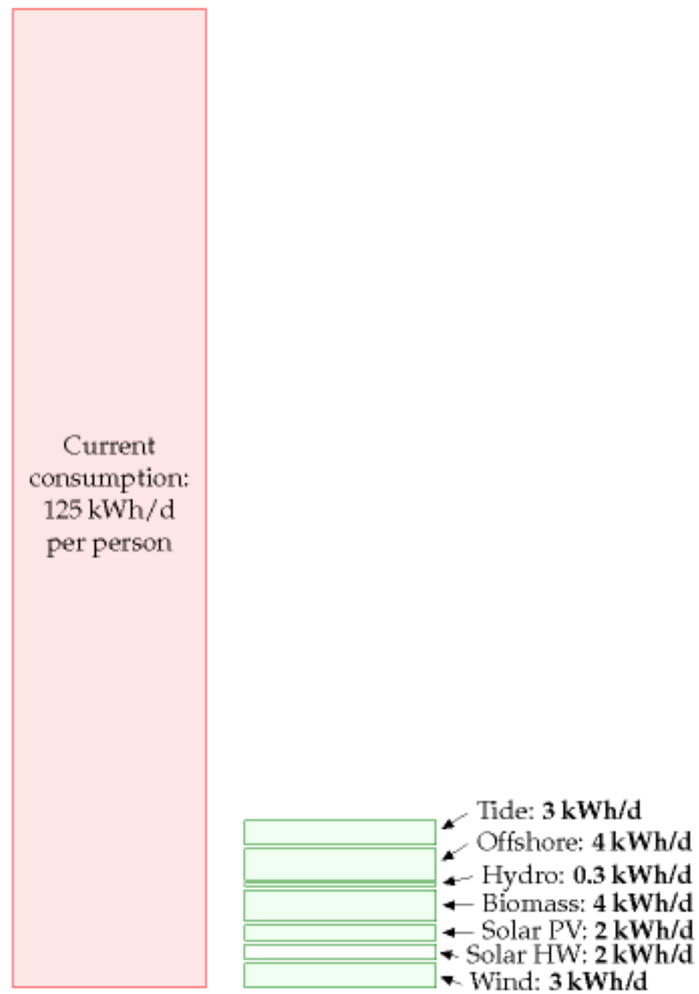
object to Midlothian Council in writing or by the eobject button on the website.

Important
During the last week of January and first week of February 2007, the Planning Department has acknowledged email objections received via the website since February 2006. The email address given to PEPA's consultant setting up the eobject site by a Planning Official was incorrect. Fortunately a backup file has been obtained but if you have not received an acknowledgement by February 8th 2007, please resubmit. A new email address has been provided and is operational. If you had already received an acknowledgement previously for objections submitted via letter / postcard, another acknowledgement would not be

A consultation exercise in full swing

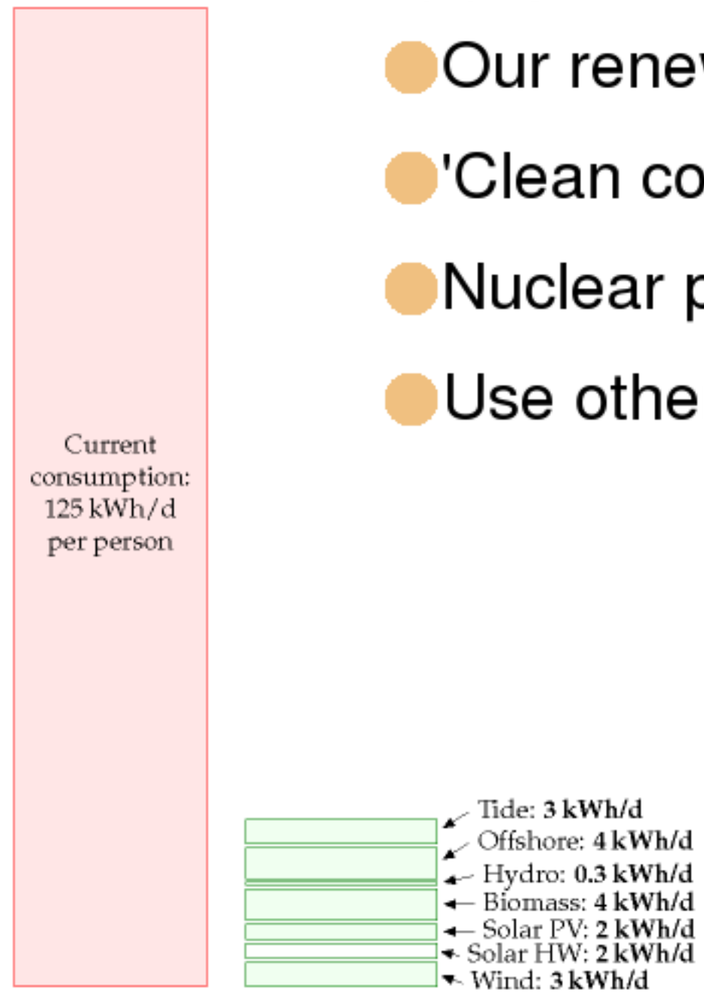
after the great British consultation exercise...



This would be a 15-fold in
rease
of renewables

How to make an energy plan that adds up

- Demand-side
  - Reduce population
  - Change lifestyle
  - Technology, efficiency
- Supply-side
  - Our renewables
  - 'Clean coal'
  - Nuclear power
  - Use other countries' renewables



Change lifestyle?

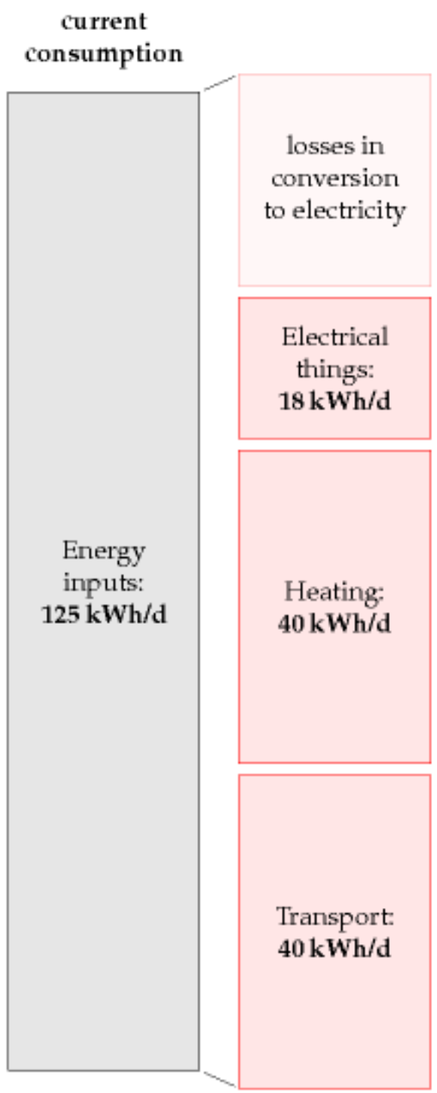
A Mitsubishi Warrior, yesterday

Some people demand the right to commit Amazingly brave acts of off-road driving

Amazing acts of testosterone-fuelled off-road driving bravery

EFFICIENCY

- Cartoon Britain, 2008



Efficient transport

Have small frontal area per person
Have small weight per person
Convert energy efficiently
Go slowly
Go steadily

© Roberto Neumiller/SOS SAHEL

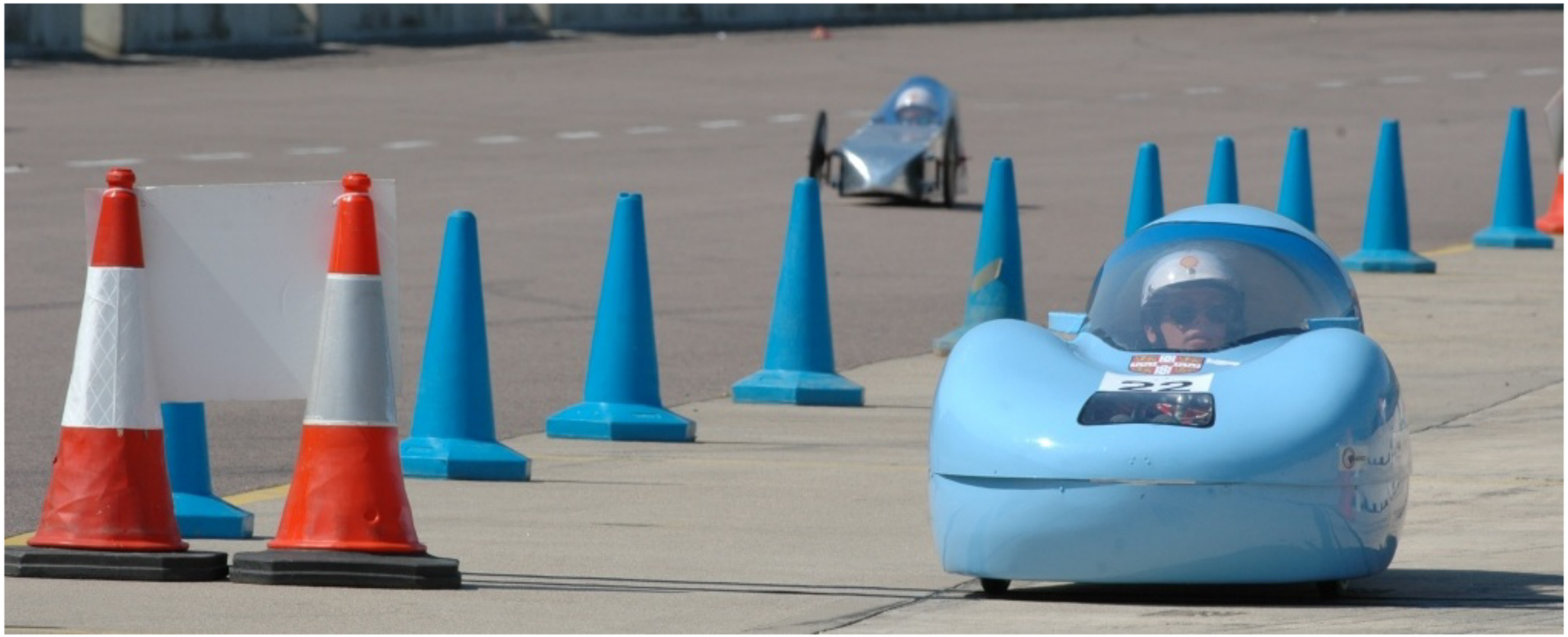
Average UK car uses
80 kWh per 100 person-km (1 person)

1 kWh per 100 person-km (3 people)

How can this consumption be reduced?

6 kWh per 100 person-km average (electric)
3 kWh per 100 person-km (electric) if full

Eco-car



1.3 kWh per 100 person-km (takes 1 teenager)

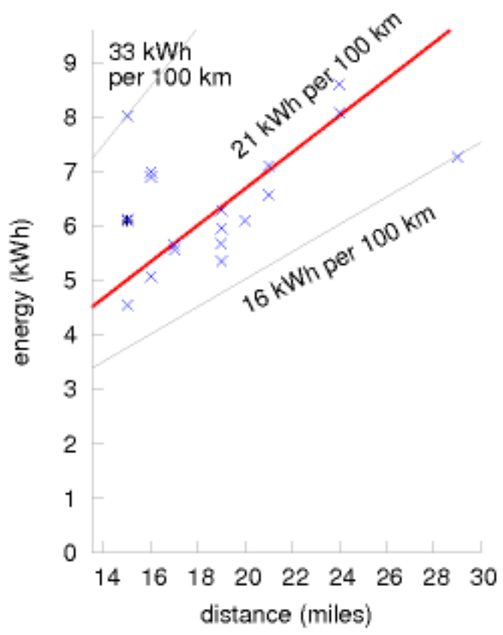
[2200 mpg]

at 15 mph

http://www.teamcrocodile.com/

Electric cars

- 21 kWh per 100 km (solo)
- equivalent to 125 miles per gallon



data from Kele Baker

G-Wiz

6 kWh per 100 km

Modec

36 kWh per 100 km

Th!nk Ox

20 kWh per 100 km

UK's first four-seater all electric production car

Thursday, 30 Apr 2009 09:03

The UK's first all electric four-seater car is available to buy from today, the Electric Car Corporation Plc (ECC) have announced.

The launch coincides with the government's announcement to support and subsidise electric car use, and their "commitment to make the UK a world leader in producing and exporting electric cars".

The motor, a Citroën C1 'ev'ie', is the first 4-seat car to be all electric, with a range of 60-70 miles when fully charged and with top speeds of around 60mph.

The C1 can be fully charged in 6-7 hours from a domestic 13 amp socket at a cost of around 90p, making it an ideal city car for either professional or domestic use.

18 kWh per 100 km (?)

Tesla, Lightning

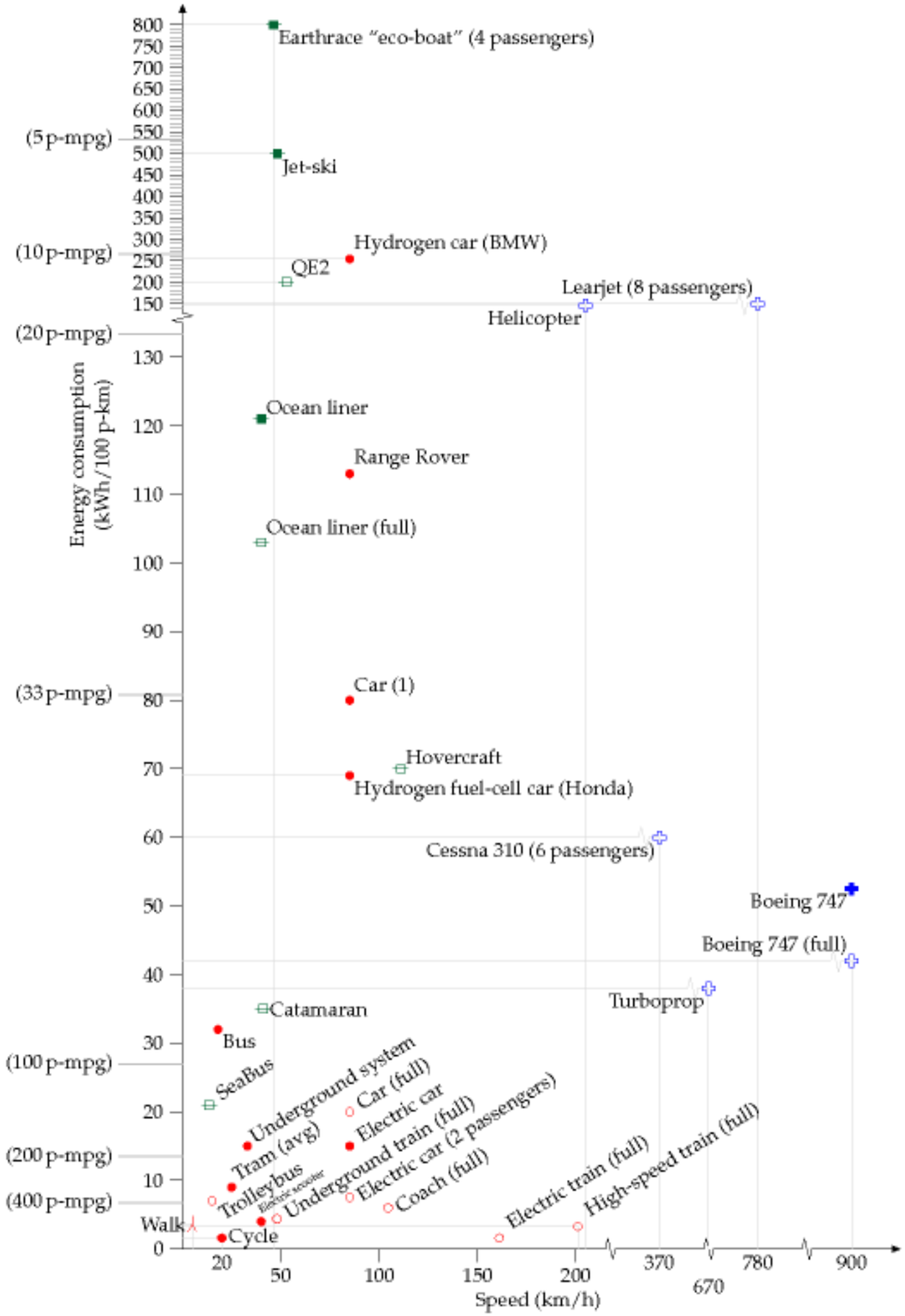
11 kWh per 100 km
www.lightningcarcompany.co.uk

15 kWh per 100 km
www.teslamotors.com

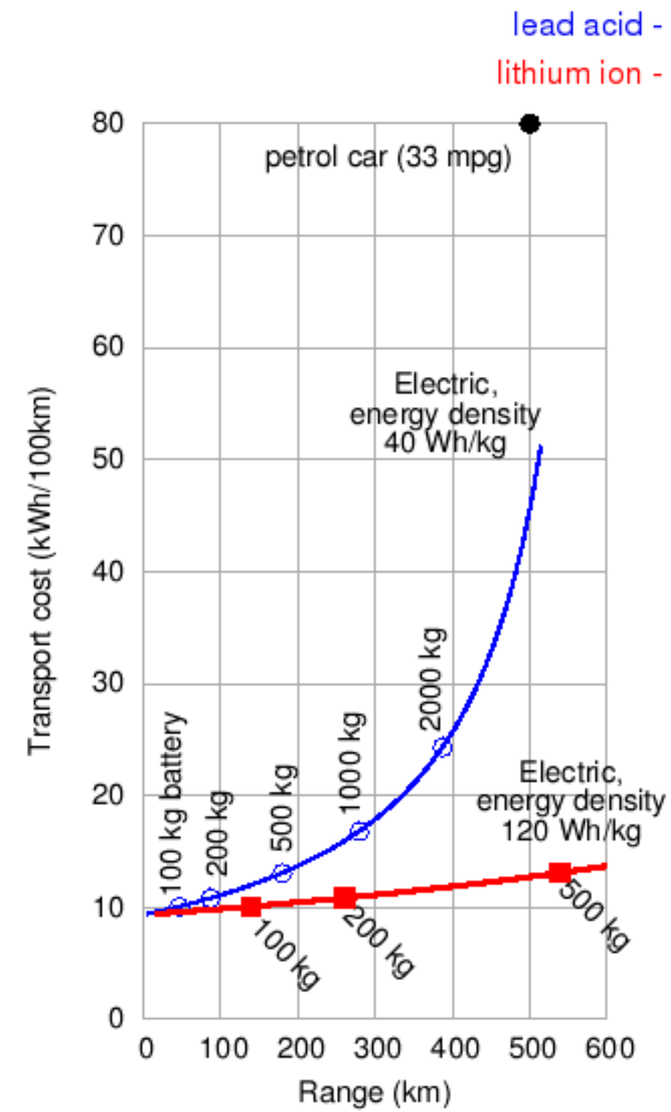
Electric scooters

3 kWh per 100 km

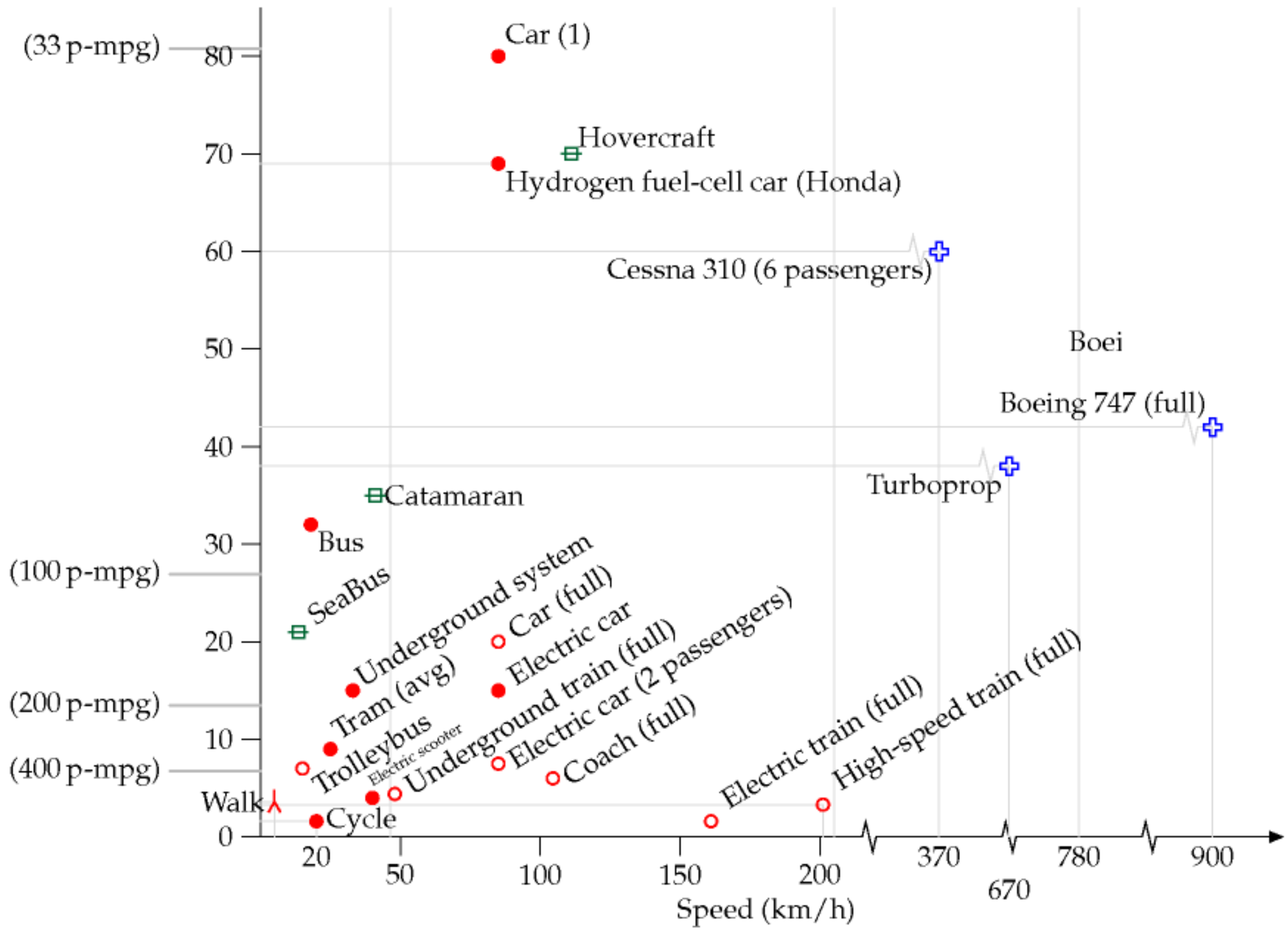
http://www.vectrix.com/



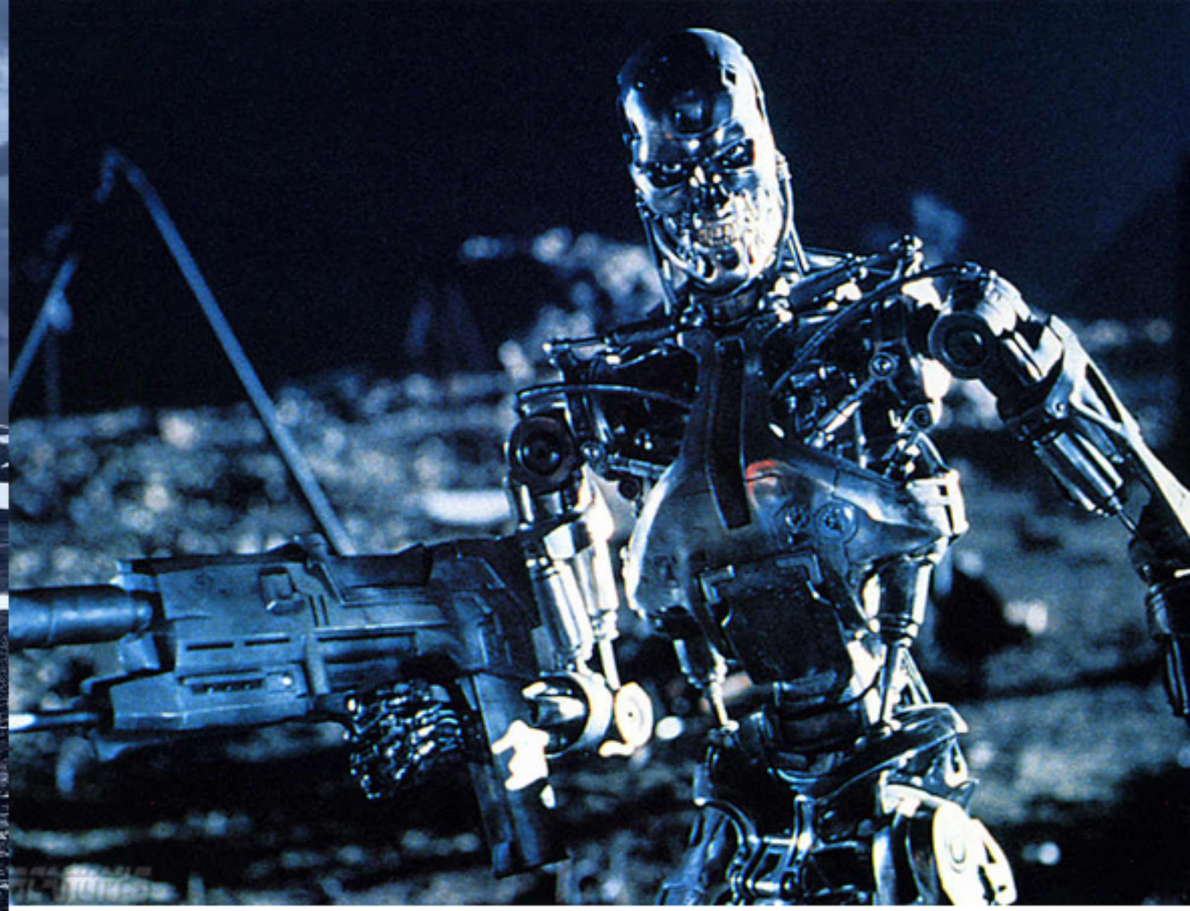
Electric car efficiency and range as a function of battery mass



Energy consumption (kWh per 100 passenger-km)



Plug-in hybrids



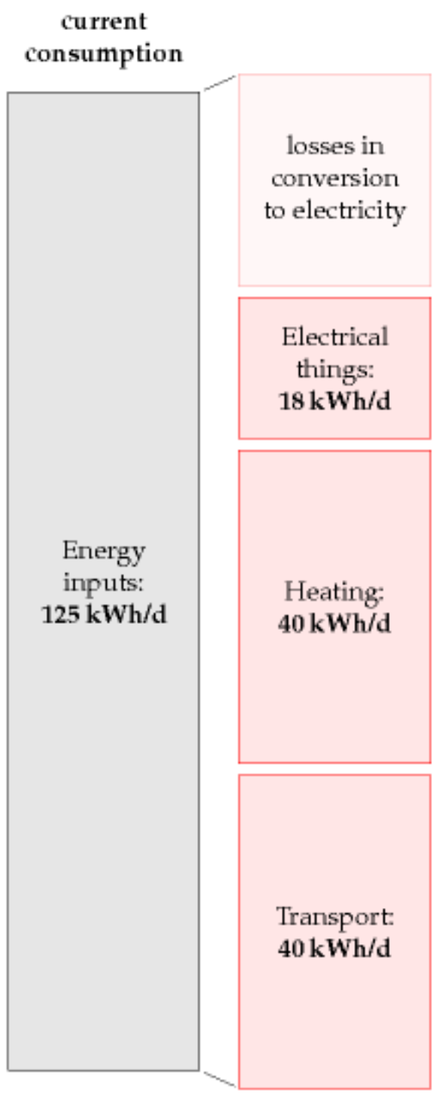
Plug-in hybrids

25 kWh per 100 km

(running on electric power alone)

EFFICIENCY

- Cartoon Britain, 2008



Efficiency for heating

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

⟵ Leakiness: 8 kWh/d/°C

$$\underset{(\mathrm{kWh/d})}{\boxed{\text{Heat loss}}} = \underset{(\mathrm{kWh/d/°C})}{\text{Leakiness}} \times \underset{(\mathrm{°C})}{\text{Average temperature difference}}$$

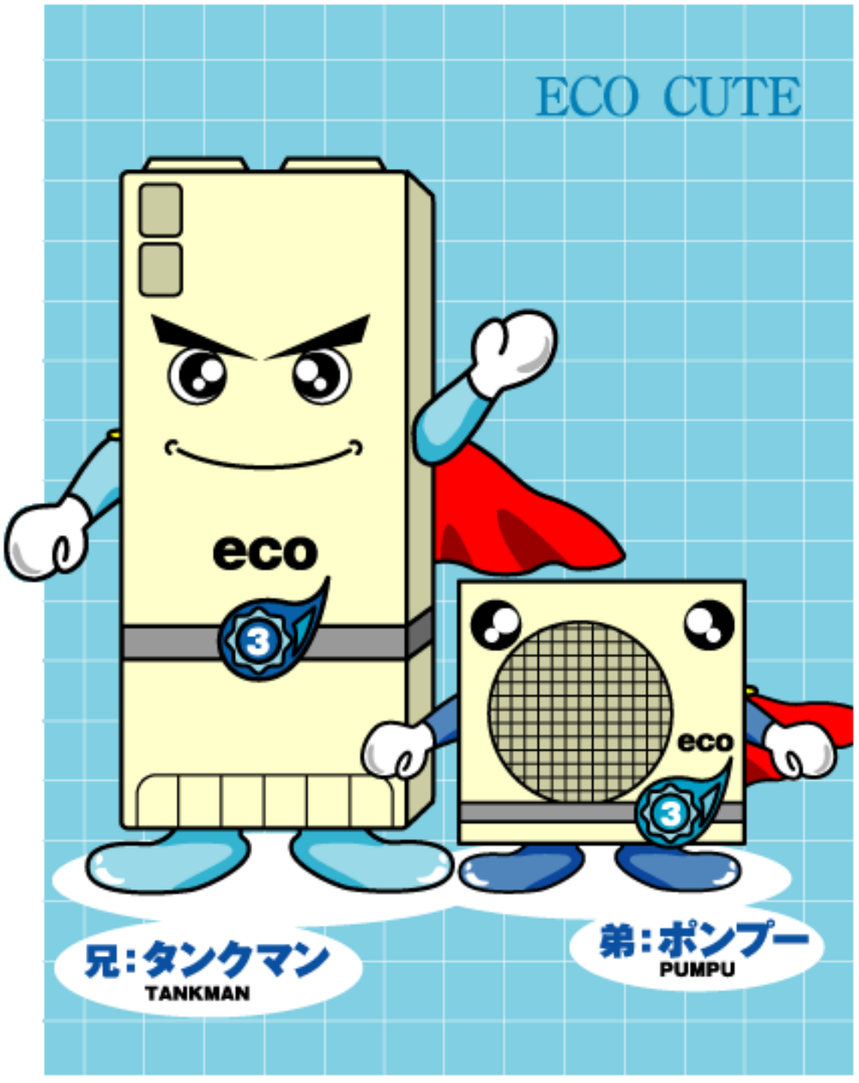
$$\text{Power required} = \boxed{\text{Heat loss}} \Big/ \text{Coefficient of performance of heat-creation}$$

Reduce leakiness

⟵ Leakiness: 8 kWh/d/°C

New leakiness: 6 kWh/d/°C

Increase coefficient of performance - use Heat pumps



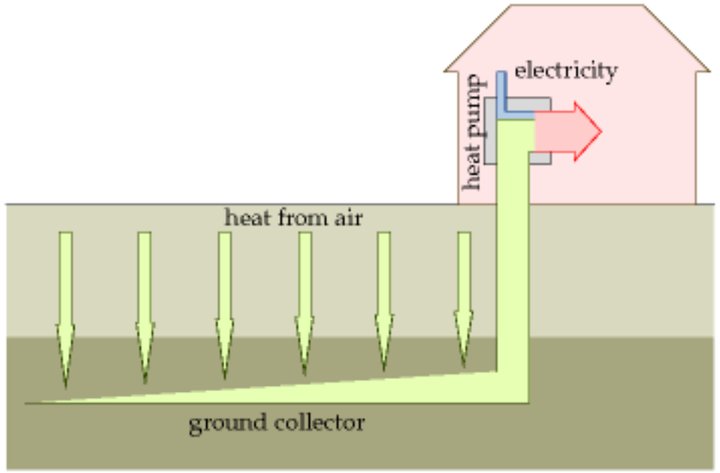
http://www.ecosystem-japan.com/

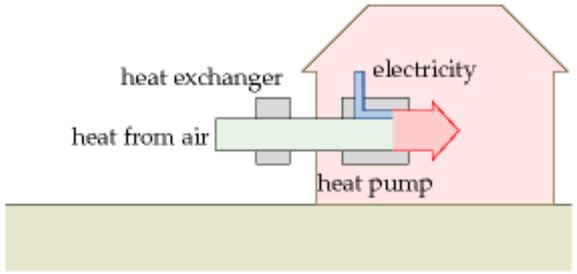
EcoCute water heater - CoP = 4.9!

$$\text{Power required} = \boxed{\text{Heat loss}} \Big/ \begin{array}{c}\text{Coefficient of performance}\\ \text{of heat-creation}\end{array}$$

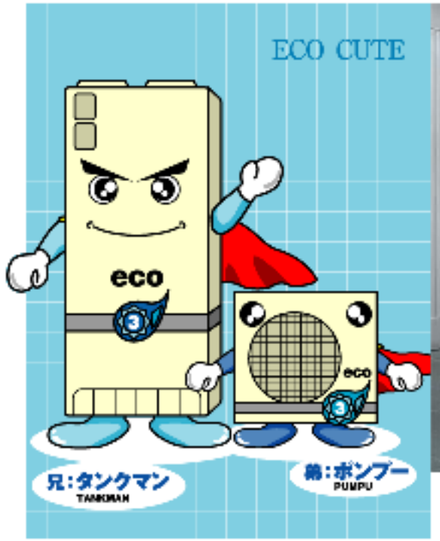
Heating without fossil fuels

- Heat pumps, powered by electricity
  - Ground-source heat pumps





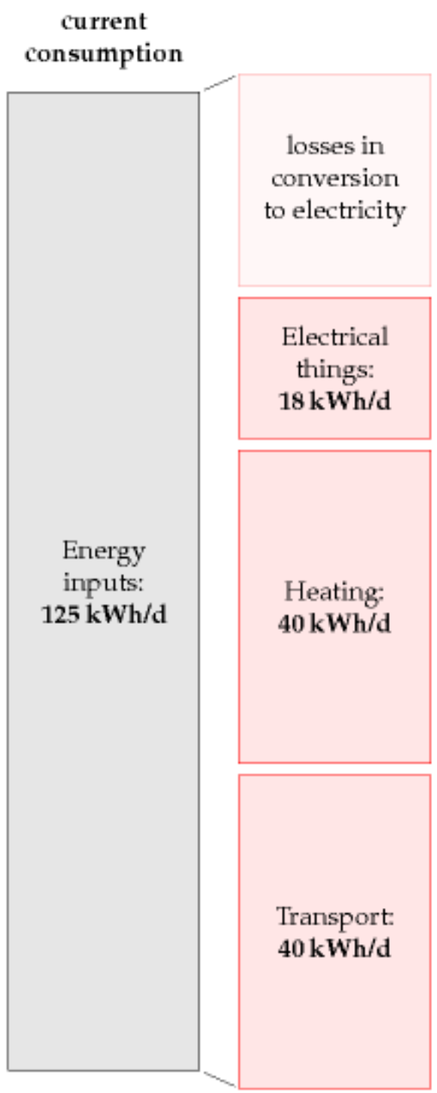
  - Air-source heat pumps



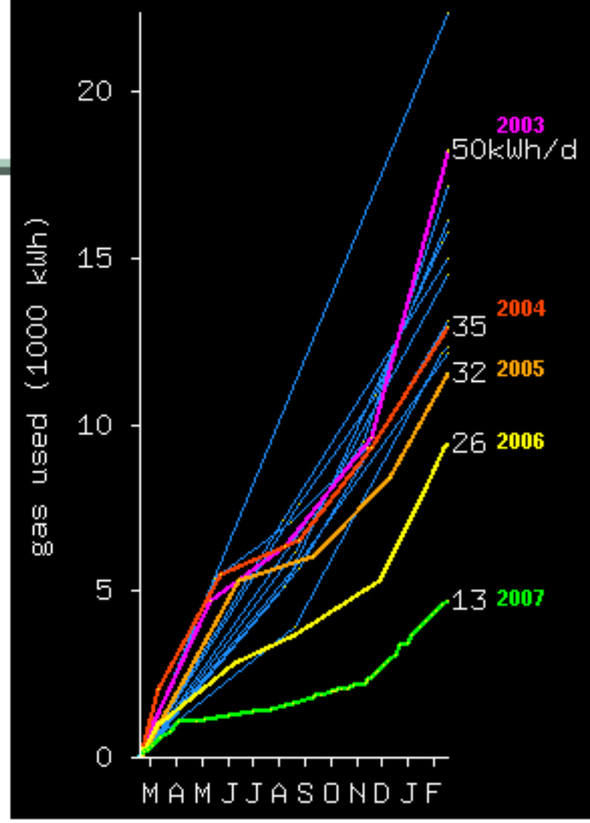
4 times more efficient than ordinary electric heating

EFFICIENCY

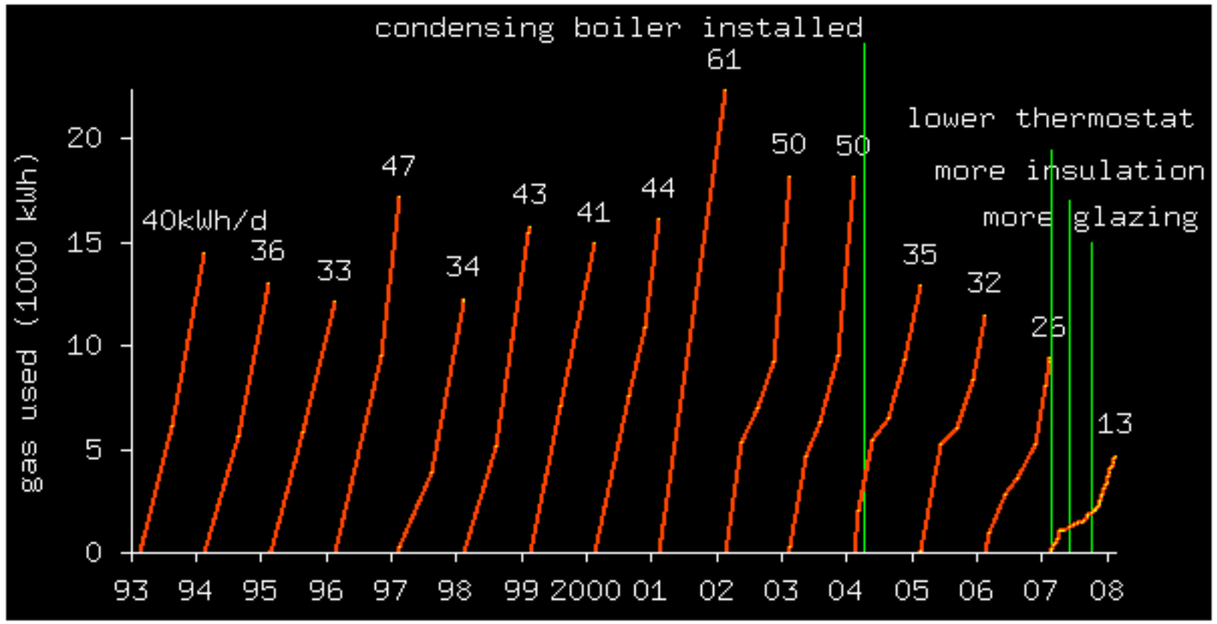
- Cartoon Britain, 2008



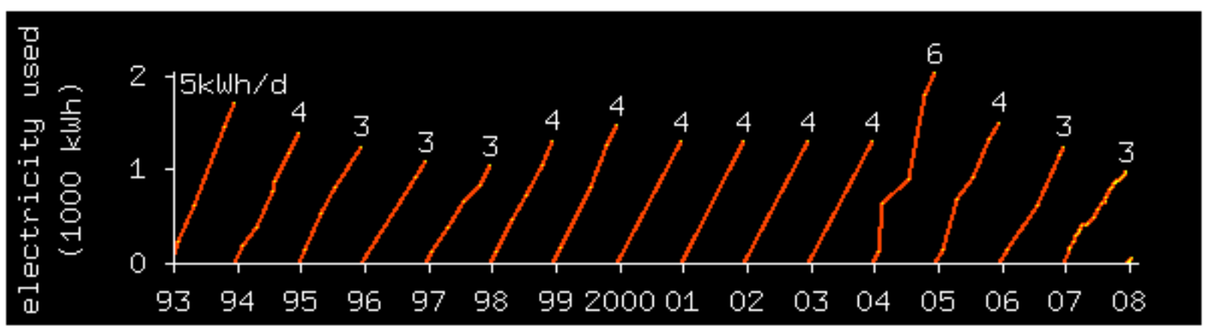
Read your meters!

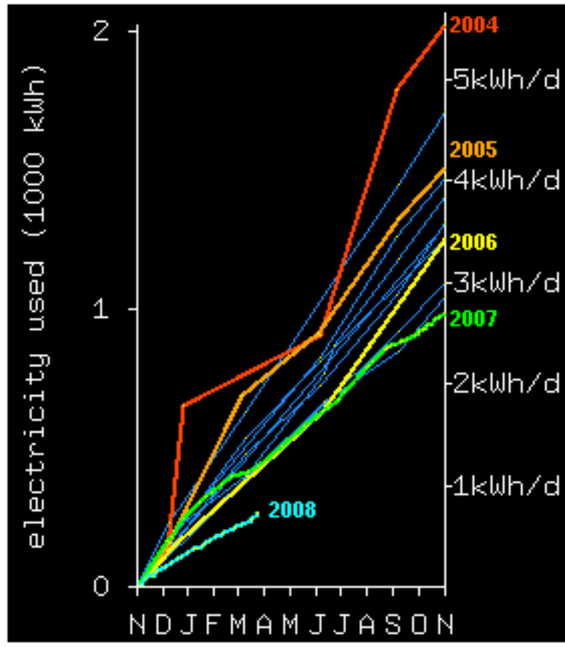


Gas



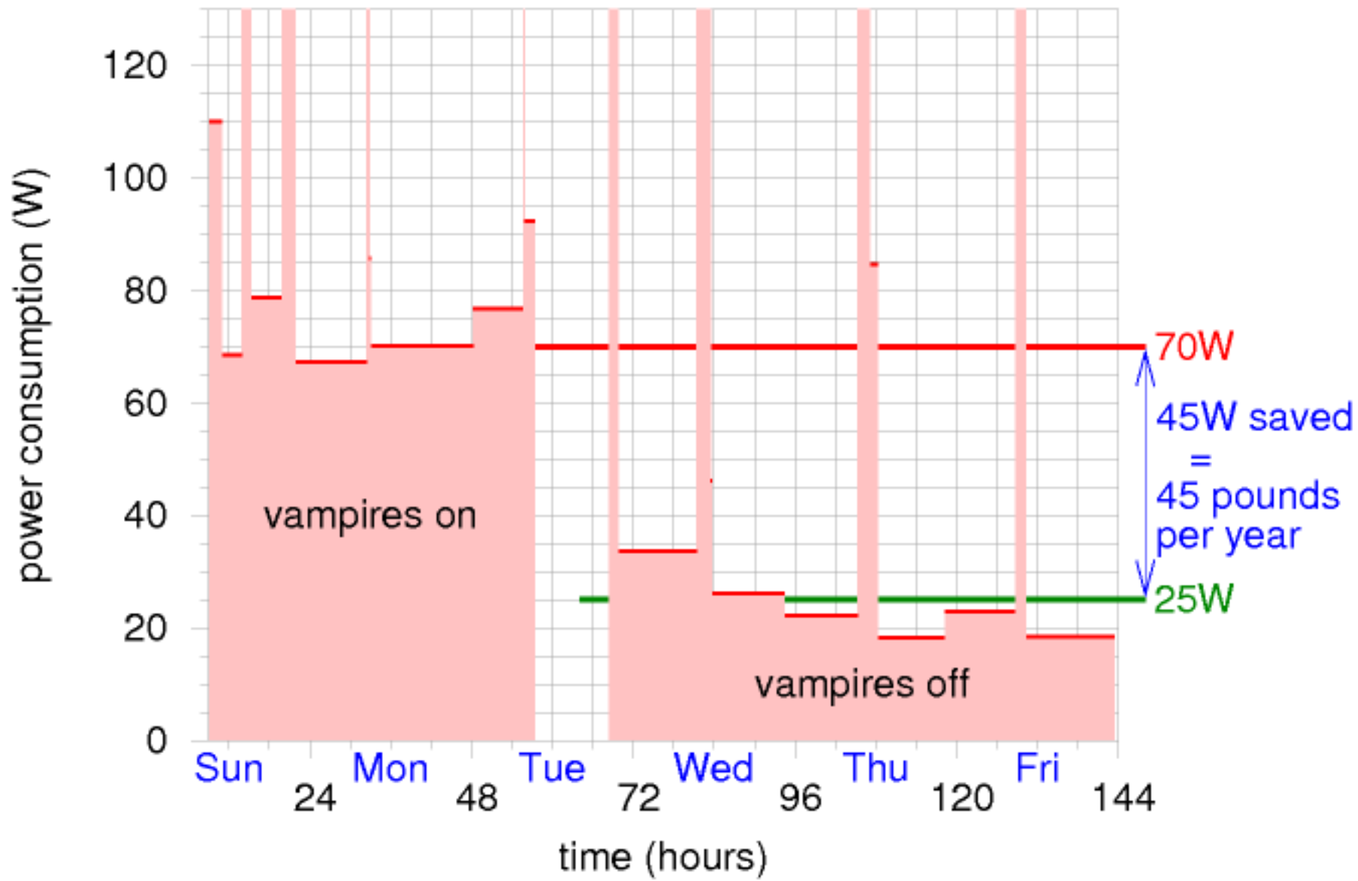
Electricity





Efficiency in the offing

- Electricity



ReadYourMeter.org

Efficiency and technology

- Jevons' paradox

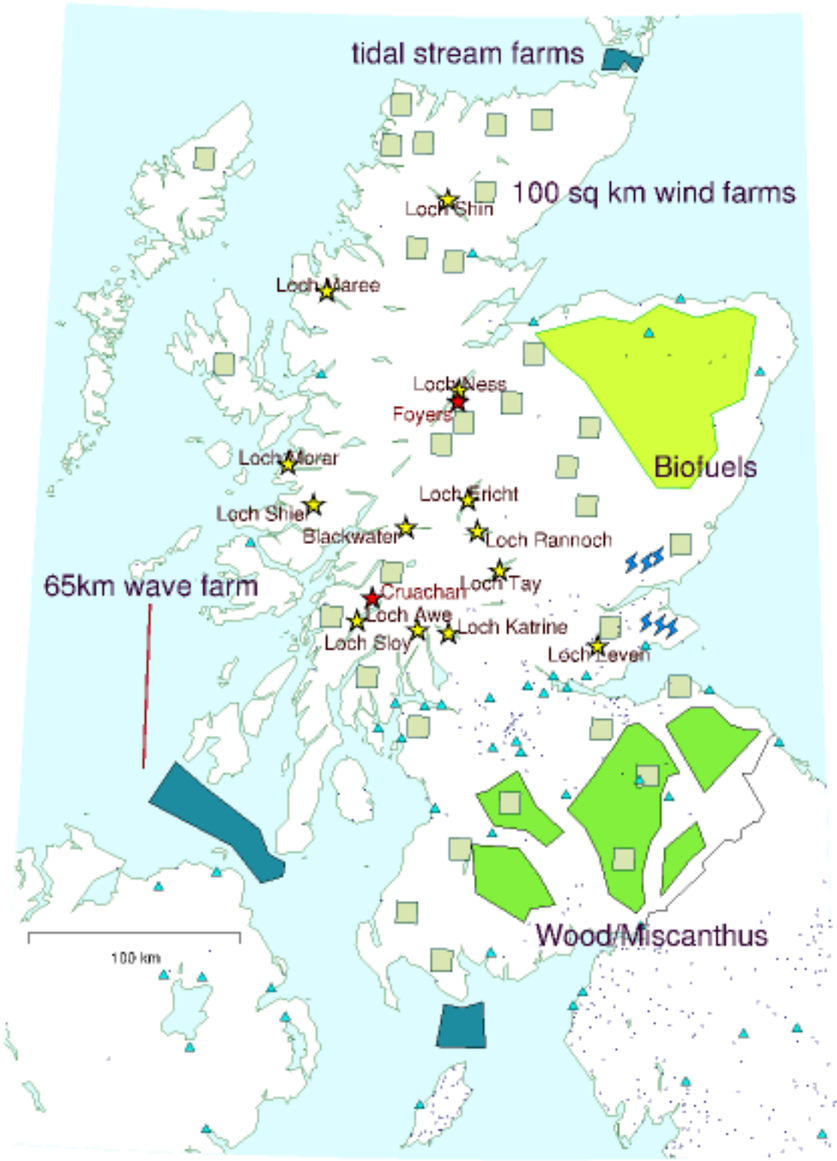
"as technological improvements increase the efficiency with which a resource is used, total consumption of that resource may increase, rather than decrease."

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.

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
    - (not combined heat and power)

  - Our renewables
  - Nuclear? (stop-gap?)
  - 'Clean coal'? (stop-gap)
  - Other people's renewables



Solar in deserts: **16 kWh/d**

Clean coal: **3**

Nuclear: **16 kWh/d**

Tide: **3.7**

Wave: **0.3**

Hydro: **0.2**

Waste: **1.1**

Pumped heat: **12 kWh/d**

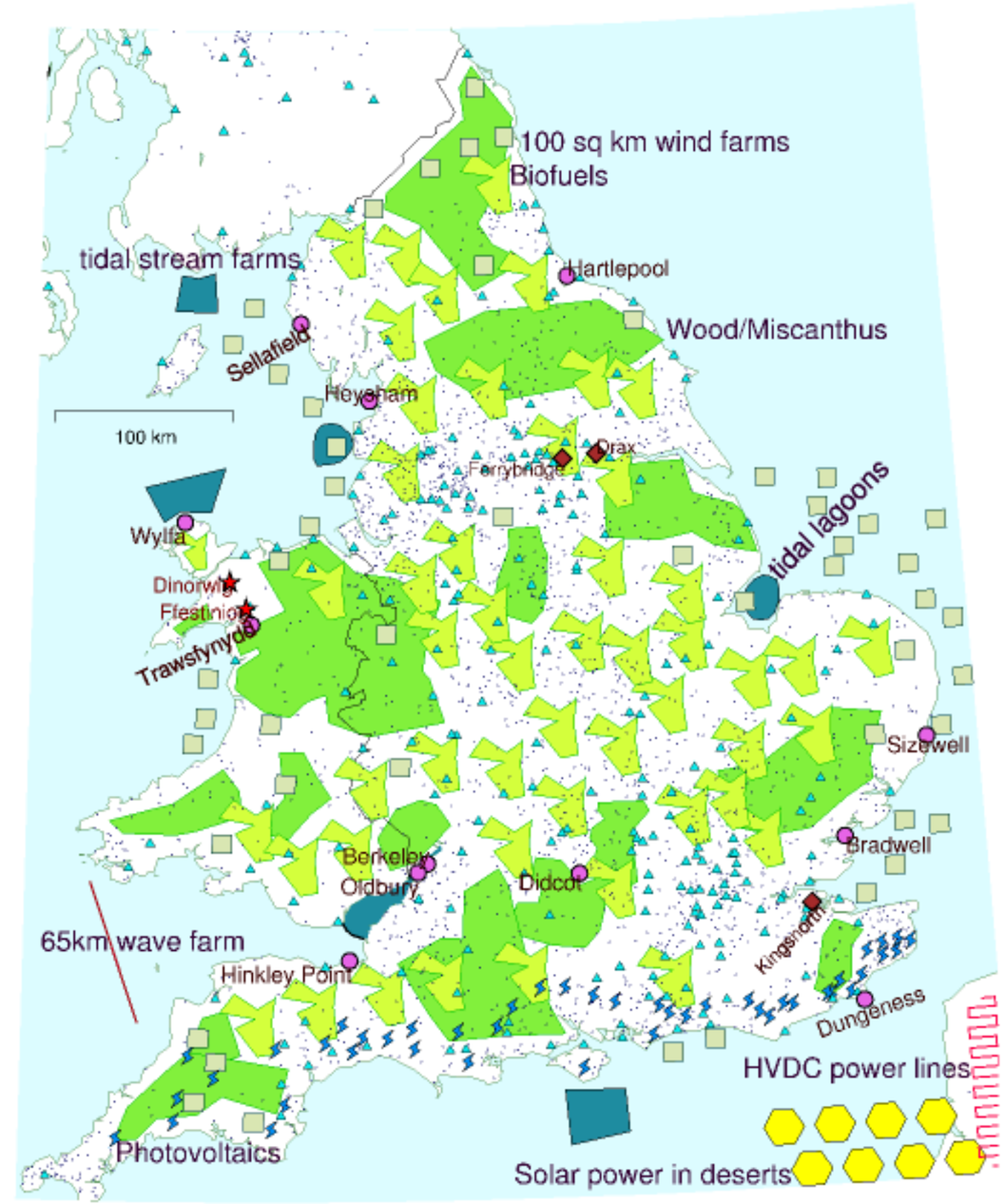
Wood: **5 kWh/d**

Solar HW: **1**

Biofuels: **2**

PV: **2**

Wind: **8**

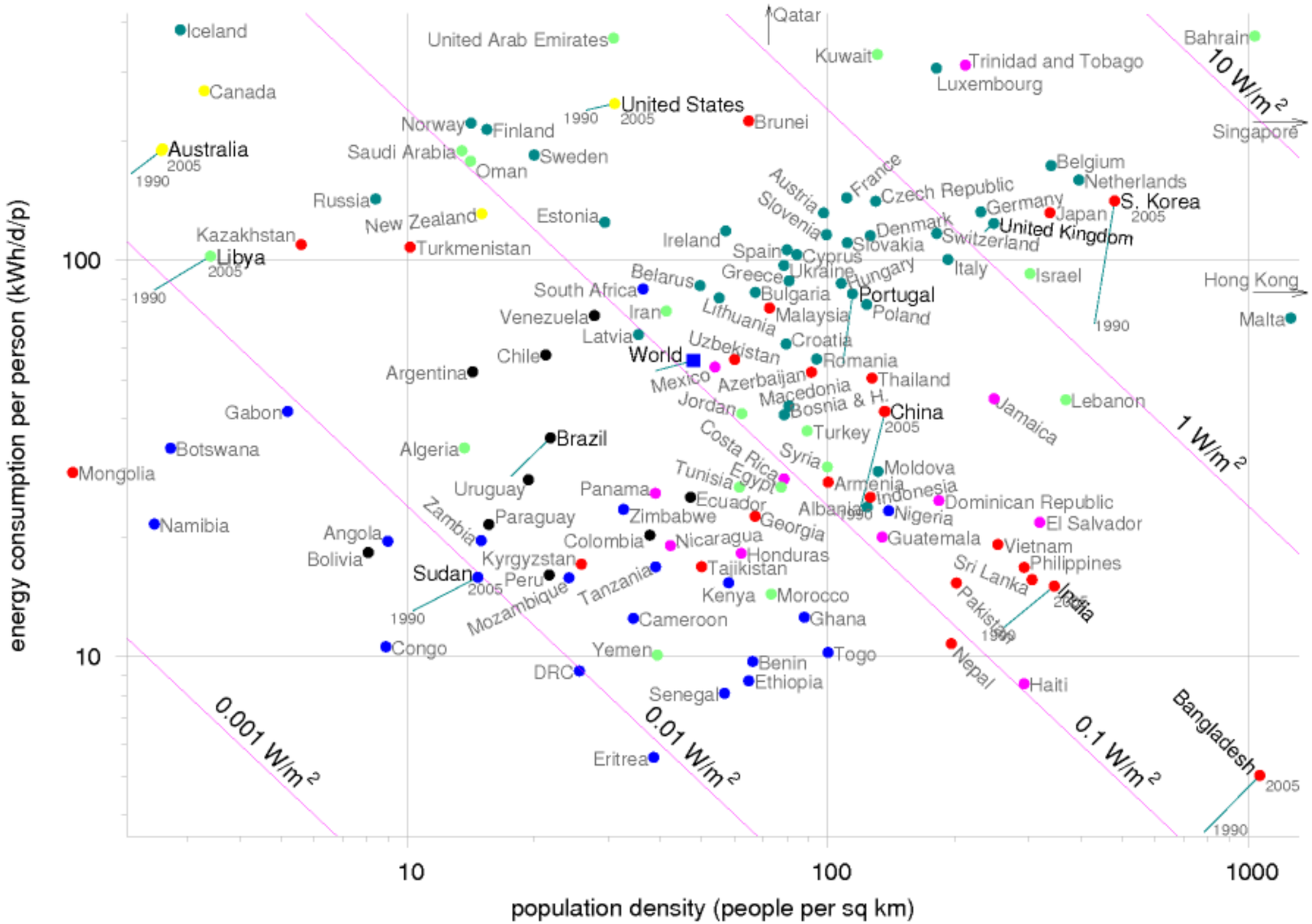


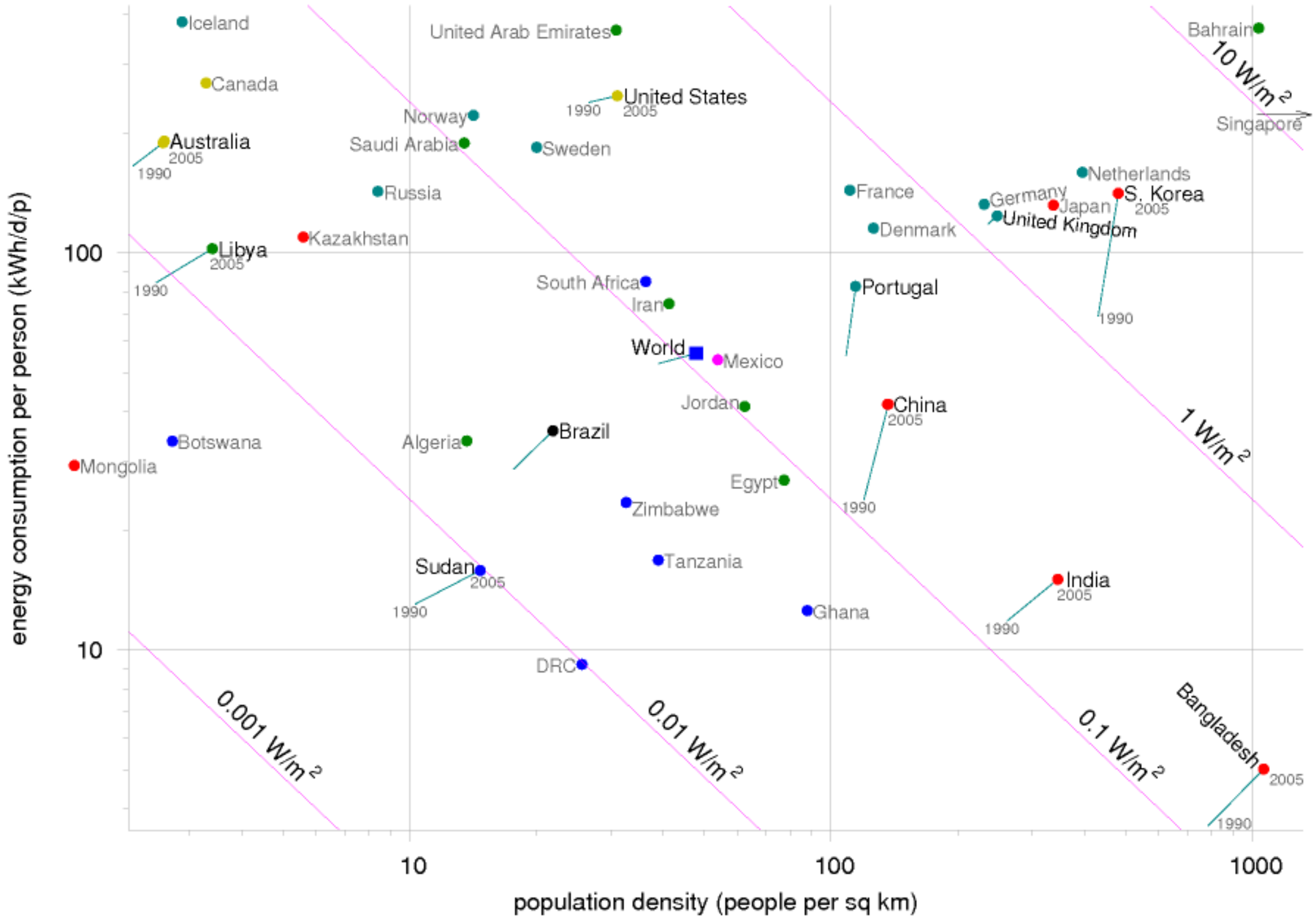
Getting off fossil fuels is not easy, but it is possible

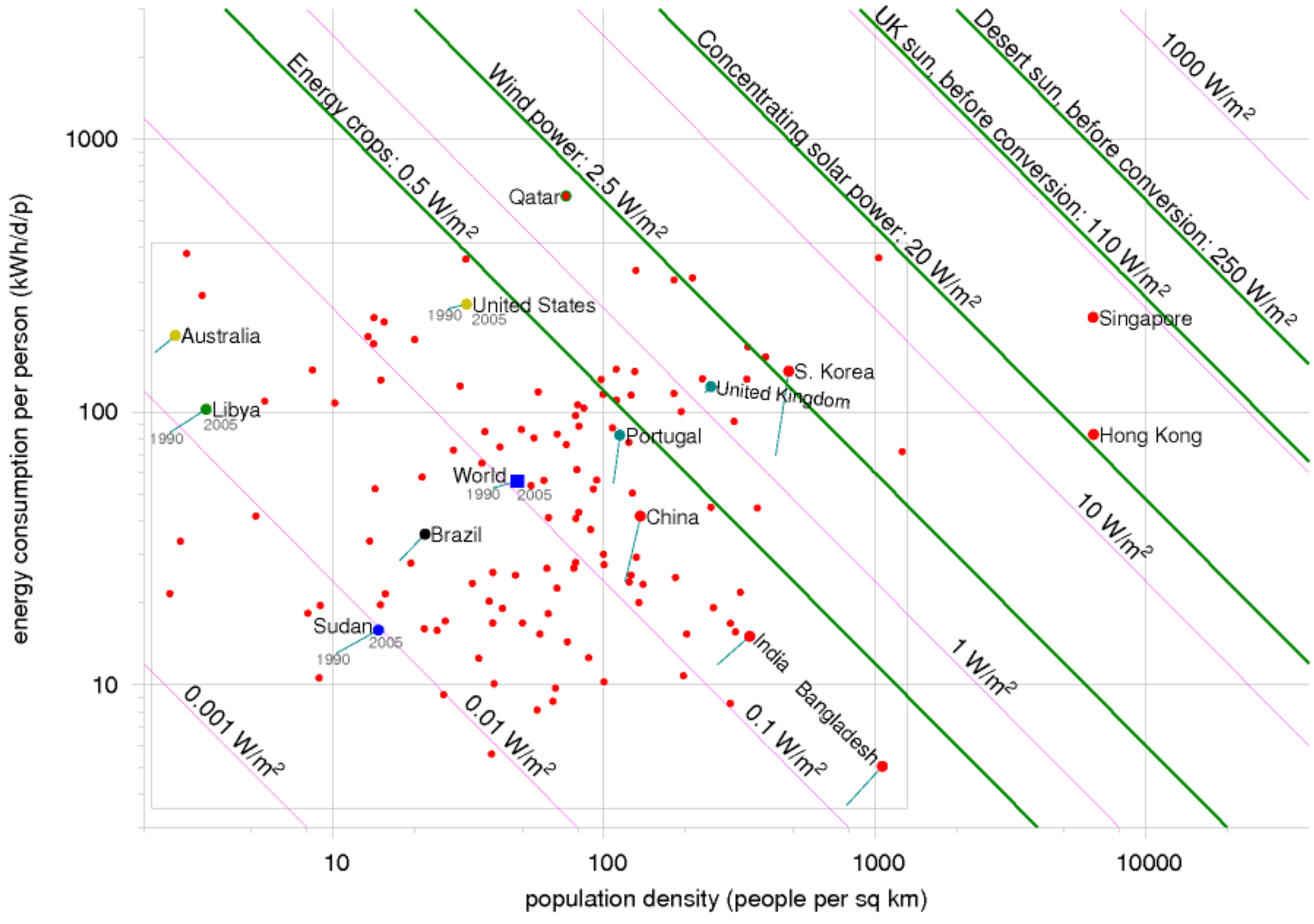
- A Plan that adds up must have some or all of:
  - country-sized renewable facilities
  - renewables from other people's countries
  - lots of nuclear power
- And efficiency too of course

'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


energy consumption per person (kWh/d/p)
population density (people per sq km)
100
10
10
100
1000
10 W/m 2
1 W/m 2
0.1 W/m 2
0.01 W/m 2
0.001 W/m 2
Iceland
Canada
Australia
2005
1990
Kazakhstan
Libya
2005
1990
United Arab Emirates
Qatar
Kuwait
Trinidad and Tobago
Luxembourg
Bahrain
Singapore
United States
1990
2005
Brunei
Norway
Finland
Saudi Arabia
Oman
Sweden
Russia
New Zealand
Estonia
Turkmenistan
Belgium
Netherlands
S. Korea
2005
Japan
Germany
United Kingdom
Austria
France
Slovenia
Czech Republic
Denmark
Slovakia
Switzerland
Ireland
Spain
Cyprus
Greece
Ukraine
Hungary
Italy
Israel
Hong Kong
Malta
Belarus
South Africa
Bulgaria
Portugal
Poland
Venezuela
Iran
Lithuania
Malaysia
Latvia
Croatia
Chile
World
Uzbekistan
Romania
Argentina
Mexico
Azerbaijan
Thailand
Macedonia
Jordan
Bosnia & H.
China
2005
Jamaica
Lebanon
Gabon
Turkey
Botswana
Algeria
Brazil
Costa Rica
Syria
Mongolia
Tunisia
Egypt
Moldova
Uruguay
Panama
Ecuador
Armenia
Indonesia
Zambia
Paraguay
Zimbabwe
Albania
Nigeria
Dominican Republic
Namibia
Angola
Colombia
Nicaragua
Georgia
El Salvador
Guatemala
Bolivia
Kyrgyzstan
Honduras
Vietnam
Sudan
Peru
Tajikistan
Philippines
Sri Lanka
Tanzania
Kenya
Morocco
Pakistan
India
2005
1990
Mozambique
Cameroon
Ghana
Congo
Yemen
Togo
Nepal
DRC
Benin
Ethiopia
Haiti
Senegal
Bangladesh
2005
1990
Eritrea


Iceland
Canada
Australia
2005
1990
Libya
2005
1990
Botswana
Mongolia
Sudan
2005
1990
United Arab Emirates
Norway
Saudi Arabia
Russia
Kazakhstan
United States
1990
2005
Sweden
South Africa
Iran
World
Mexico
Jordan
Algeria
Brazil
Egypt
Zimbabwe
Tanzania
Ghana
DRC
France
Denmark
Portugal
China
2005
1990
Germany
Japan
United Kingdom
Netherlands
S. Korea
2005
1990
India
2005
1990
Bahrain
Singapore
Bangladesh
2005
1990
10 W/m 2
1 W/m 2
0.1 W/m 2
0.01 W/m 2
0.001 W/m 2
100
10
10
100
1000
energy consumption per person (kWh/d/p)
population density (people per sq km)


Energy crops: 0.5 W/m²
Wind power: 2.5 W/m²
Concentrating solar power: 20 W/m²
UK sun, before conversion: 110 W/m²
Desert sun, before conversion: 250 W/m²
1000 W/m²
10 W/m²
1 W/m²
0.1 W/m²
0.01 W/m²
0.001 W/m²
Qatar
United States
1990
2005
Australia
Libya
2005
1990
S. Korea
United Kingdom
Singapore
Hong Kong
Portugal
World
1990
2005
China
Brazil
Sudan
2005
1990
India
Bangladesh
1000
100
10
10
100
1000
10000
energy consumption per person (kWh/d/p)
population density (people per sq km)