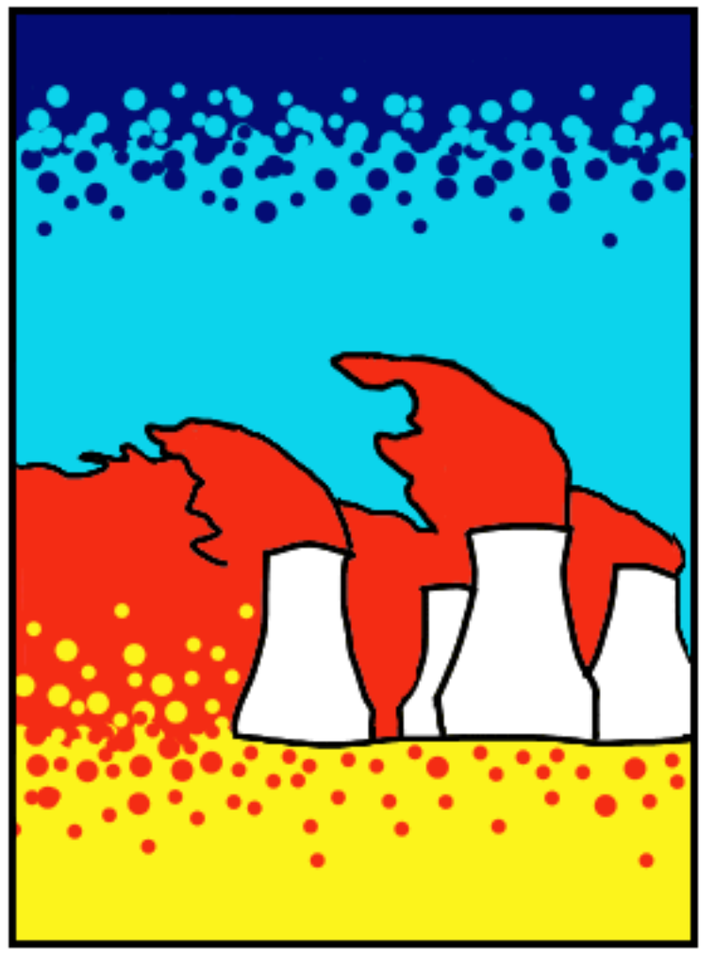
Cambridge February 2008

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

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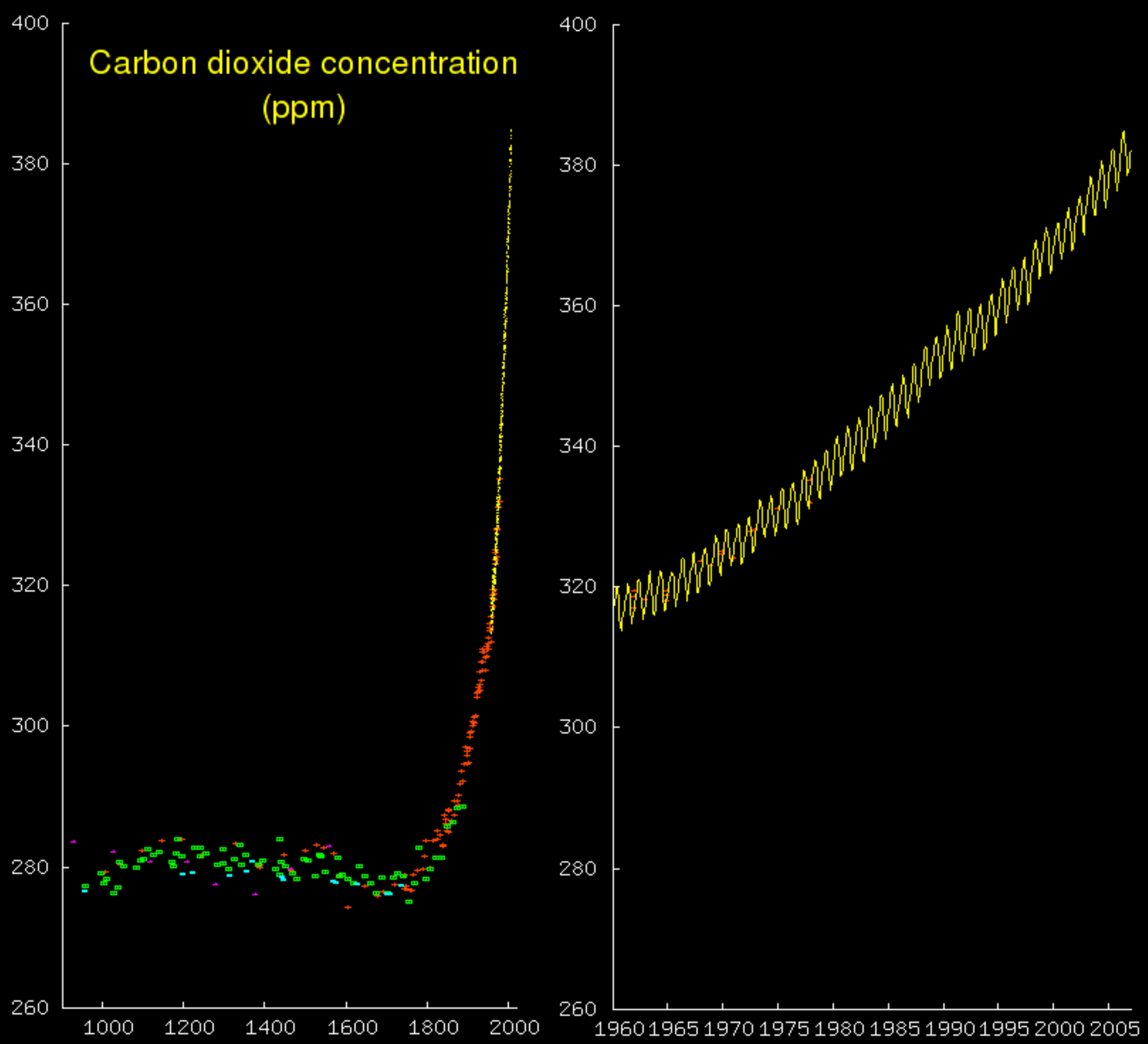
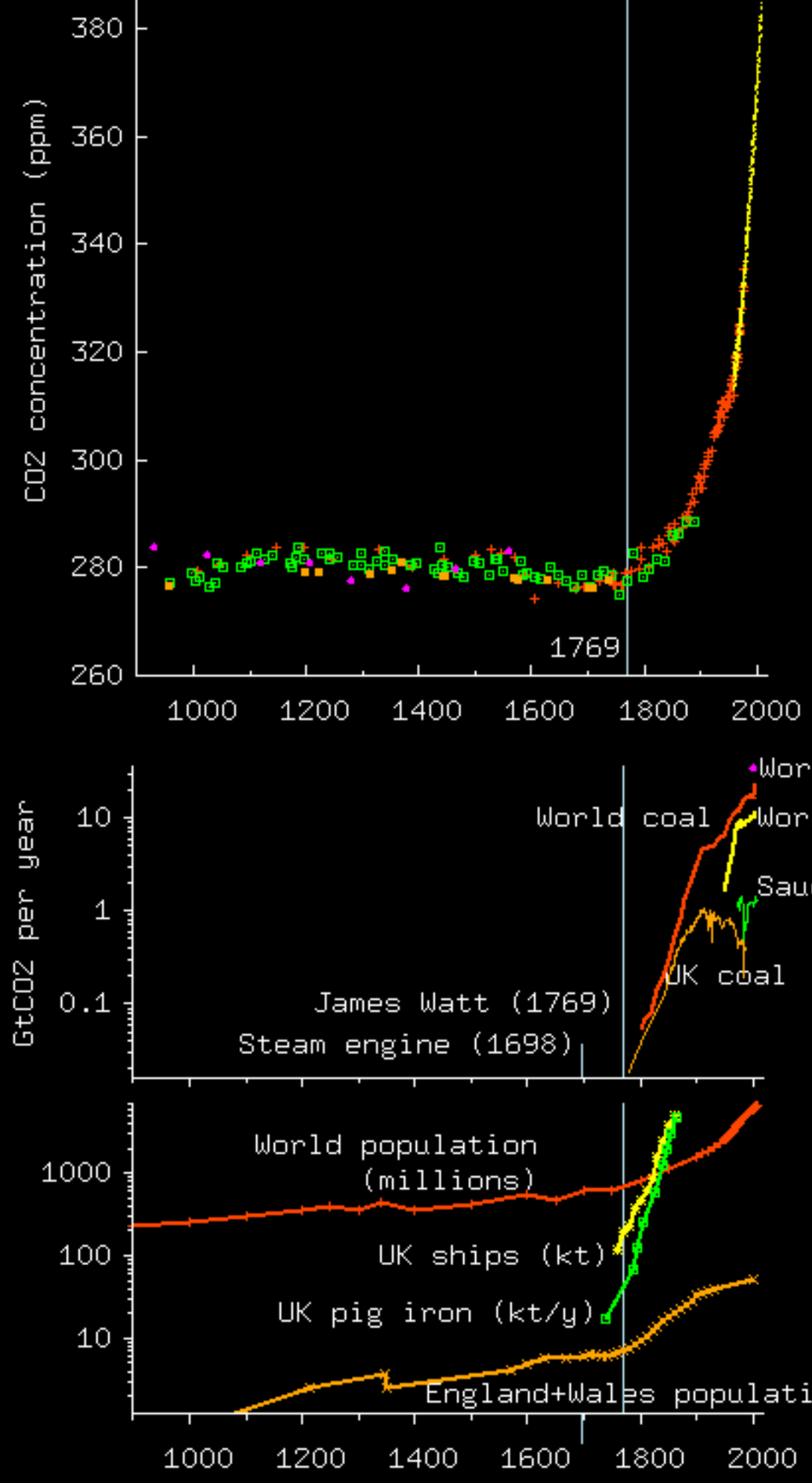
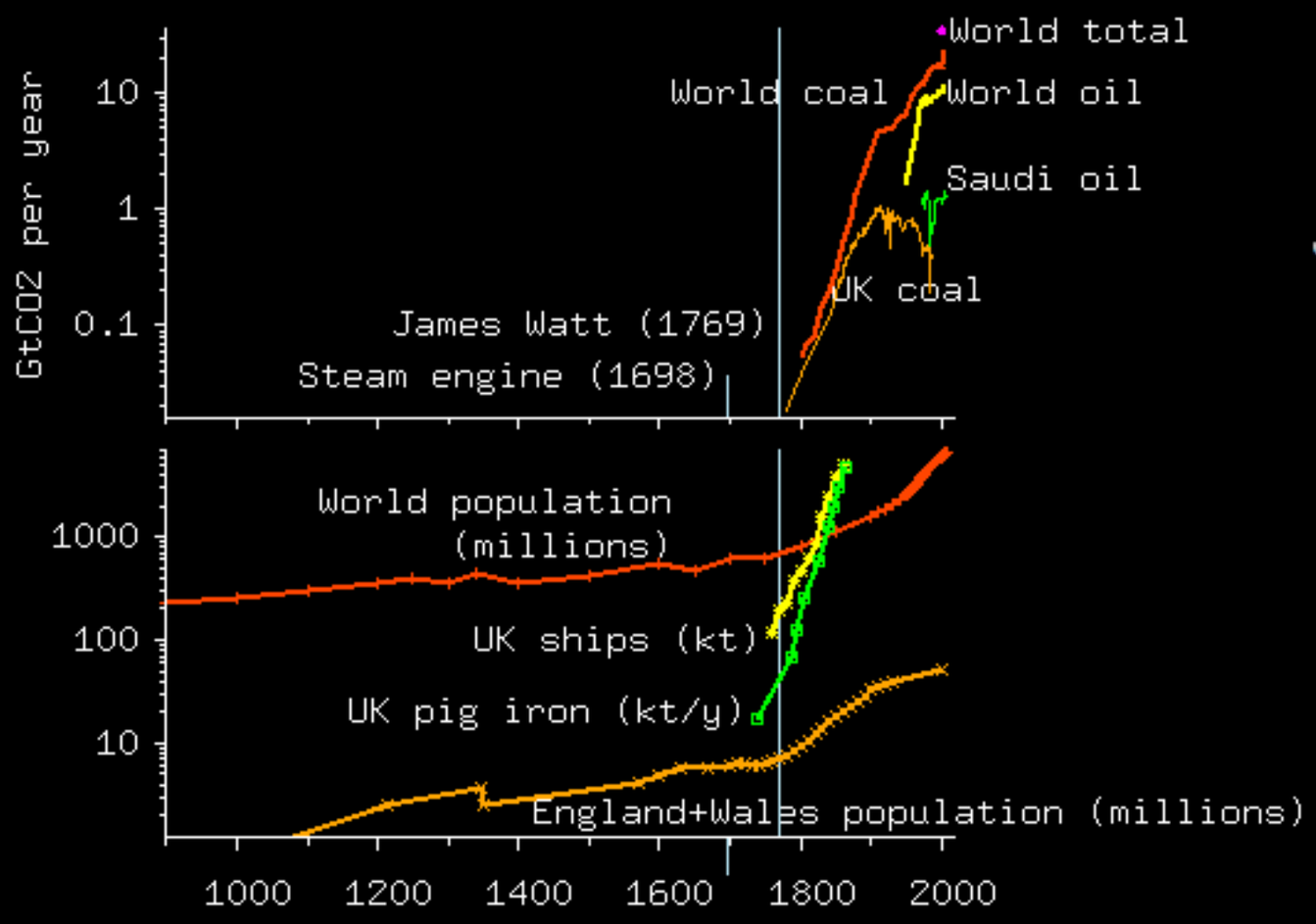
We need to get off fossil fuels

- 1: fossil fuels will run out
  - + maybe future generations would prefer to do something smarter with them
- 2: climate change
- 3: security of supply

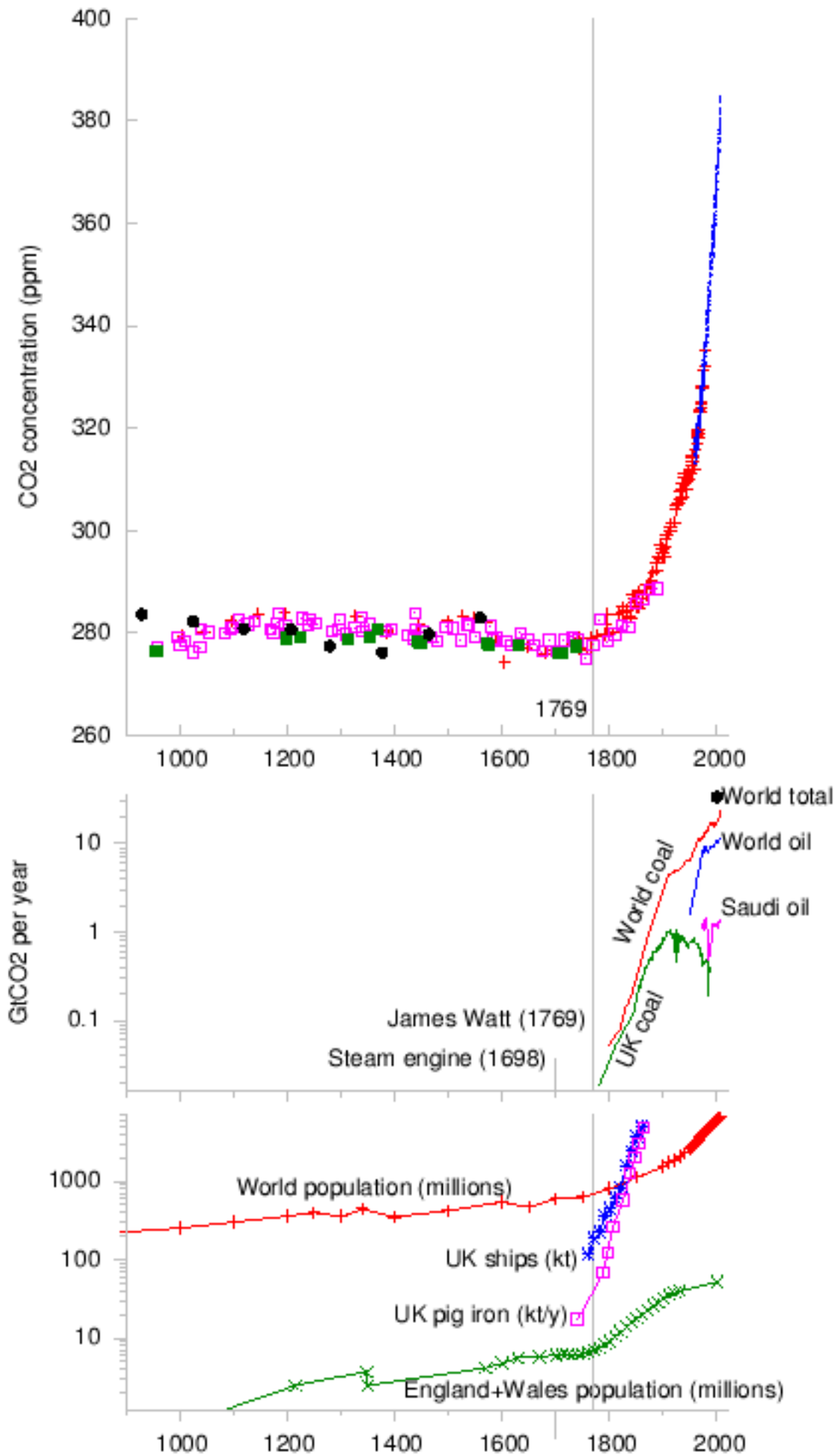


Sources: Keeling and Whorf (2005); Neftel et al (1994); Etheridge et al (1998); Siegenthaler et al (2005); Indermuhle et al (1999)





James Watt (1769)



James Watt (1769)

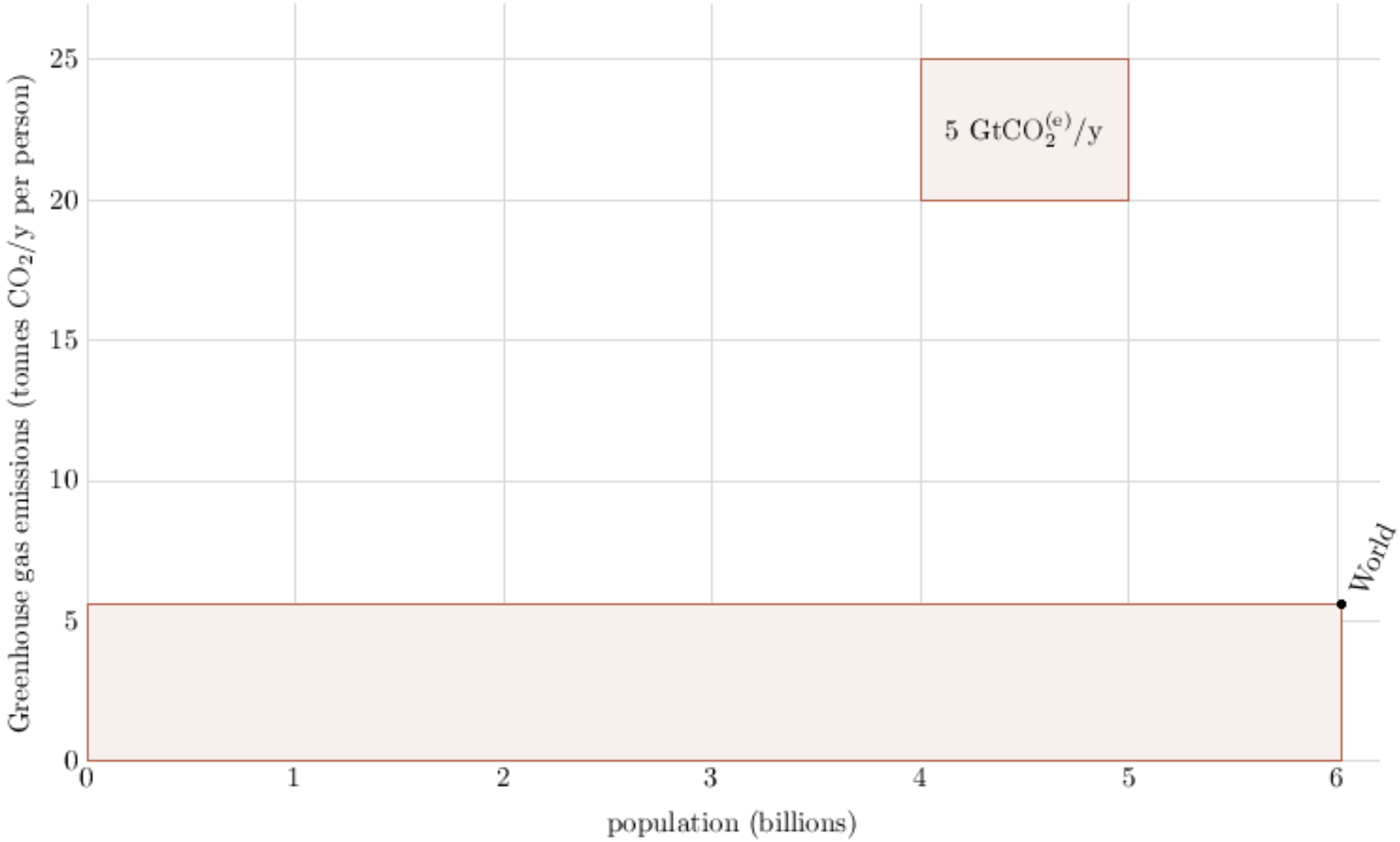
'Security of supply'

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

Photo by Terry Cavner

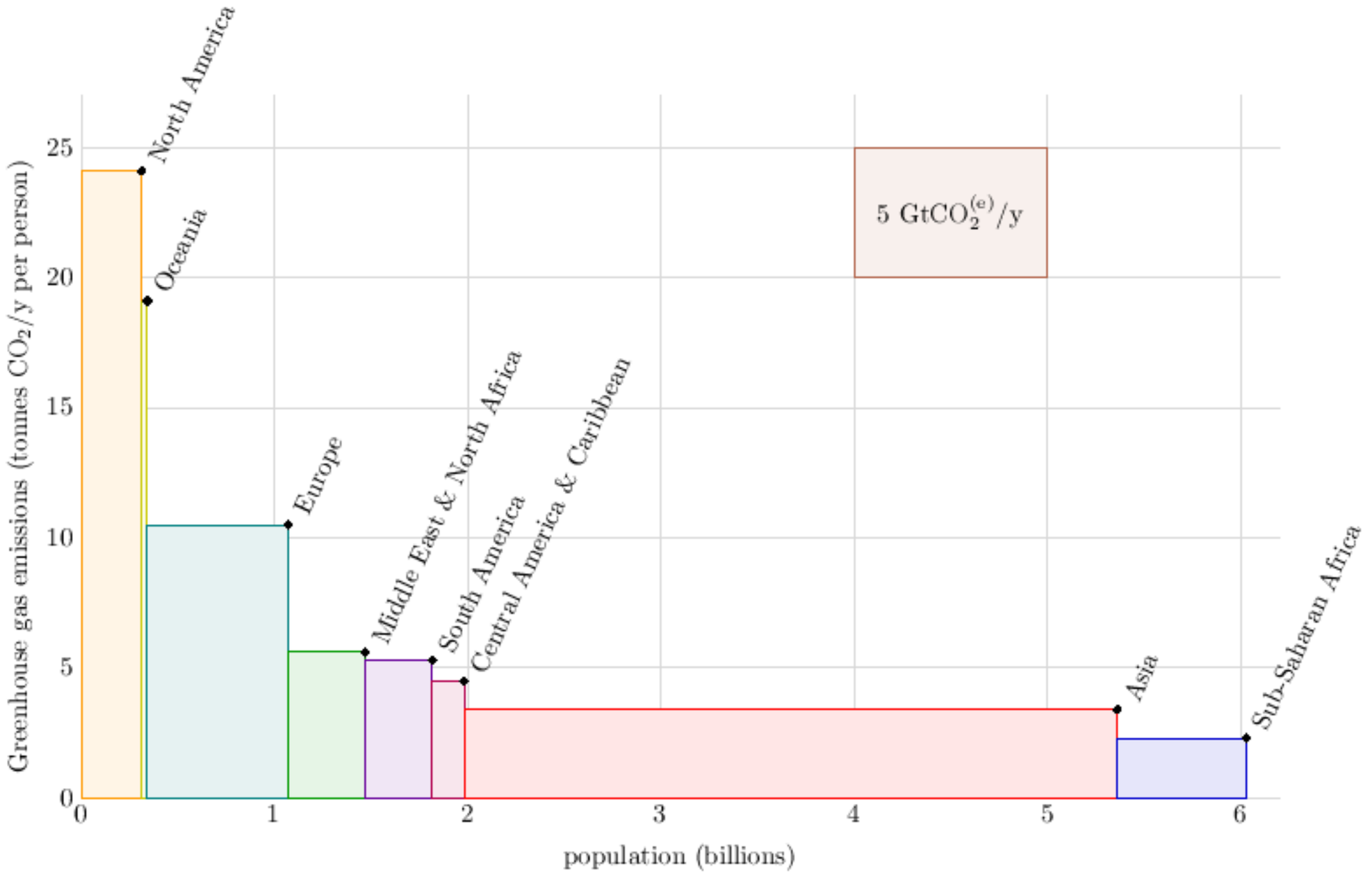
Something must be done!

17g



$$\text{Total GHG emissions } (2000) = 34\,\text{GtCO}_2^{(e)}$$

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



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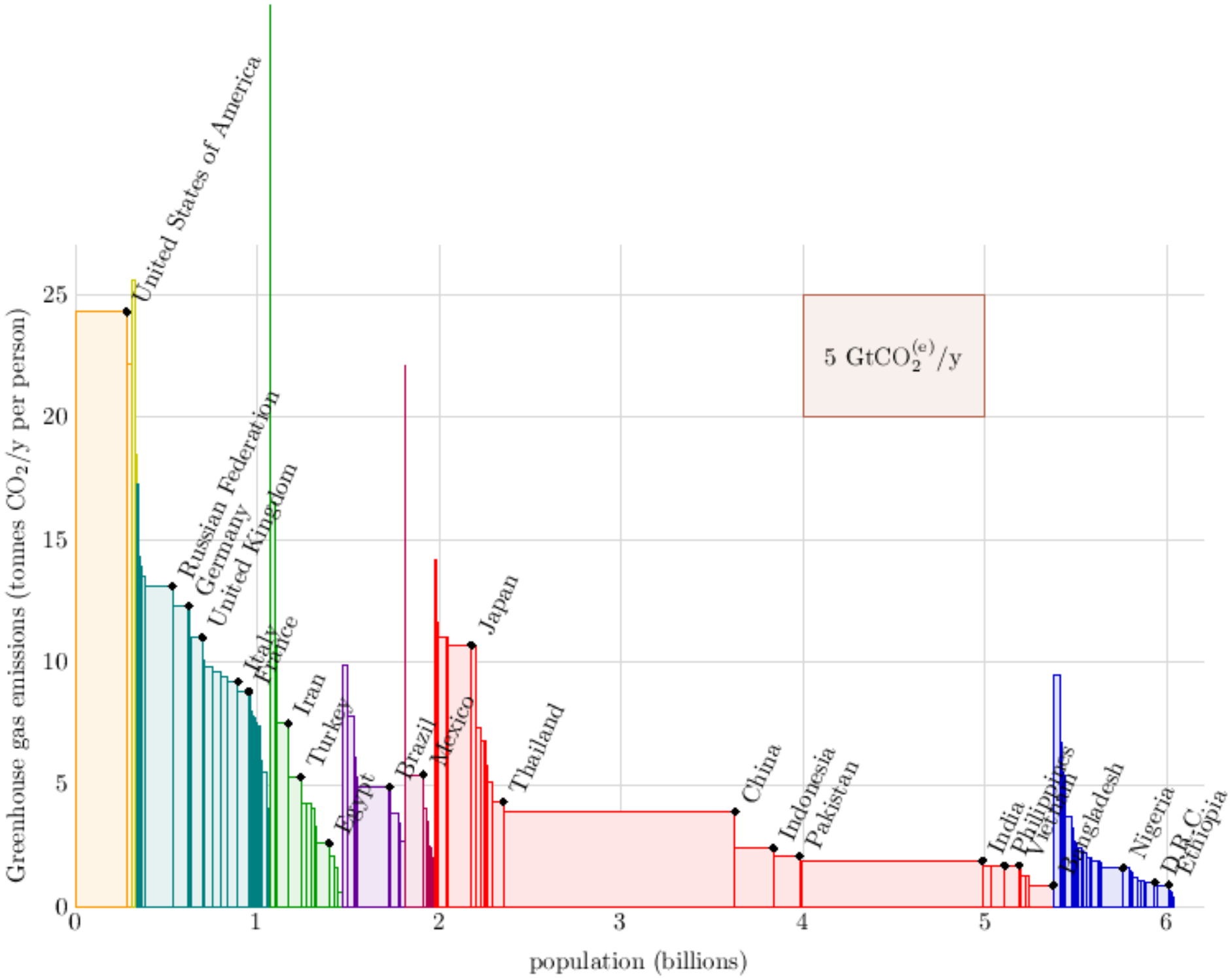

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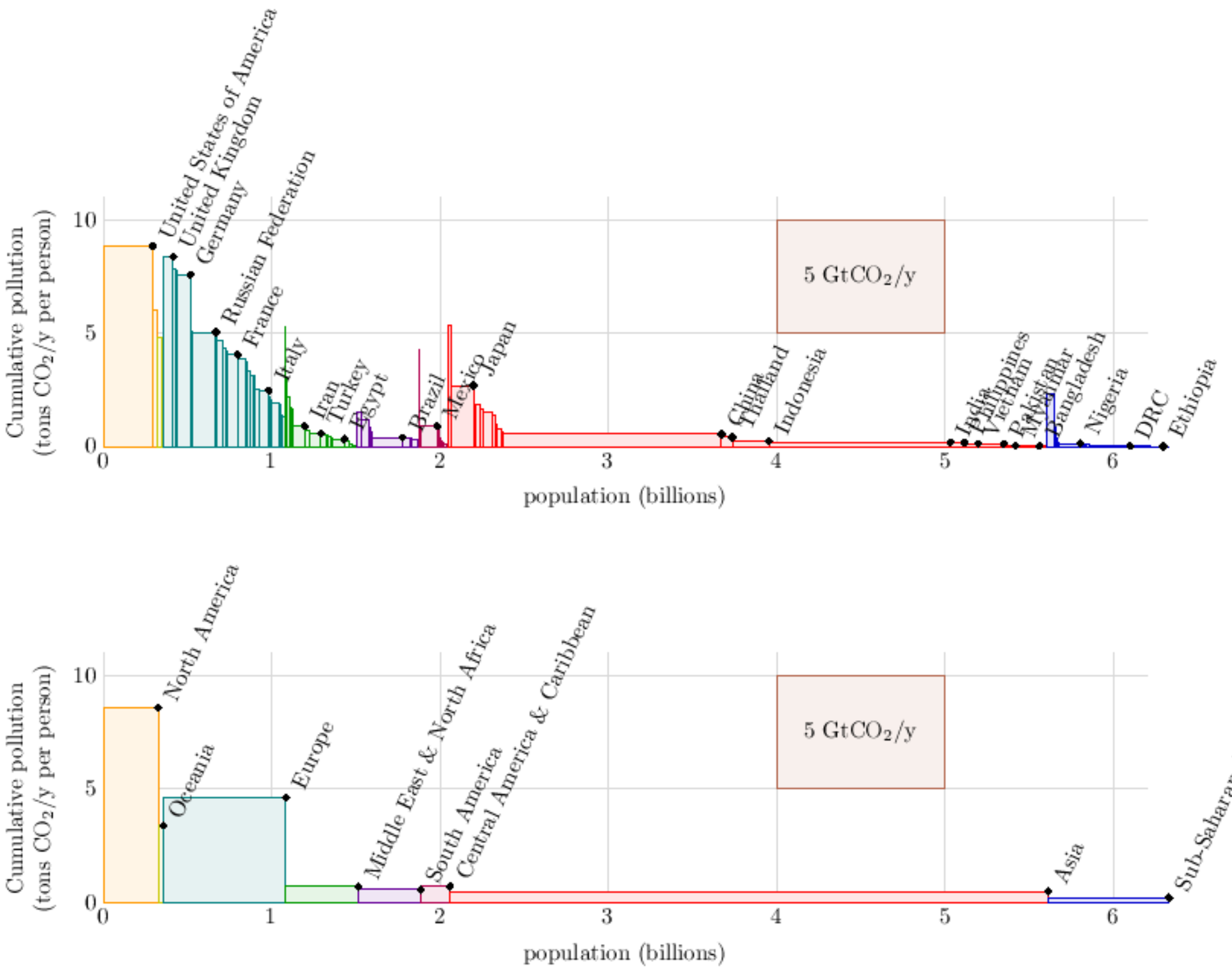
17g
Qatar, United Arab Emirates, and Kuwait

Cumulative emissions (average for 1880–2004) – CO_2 only

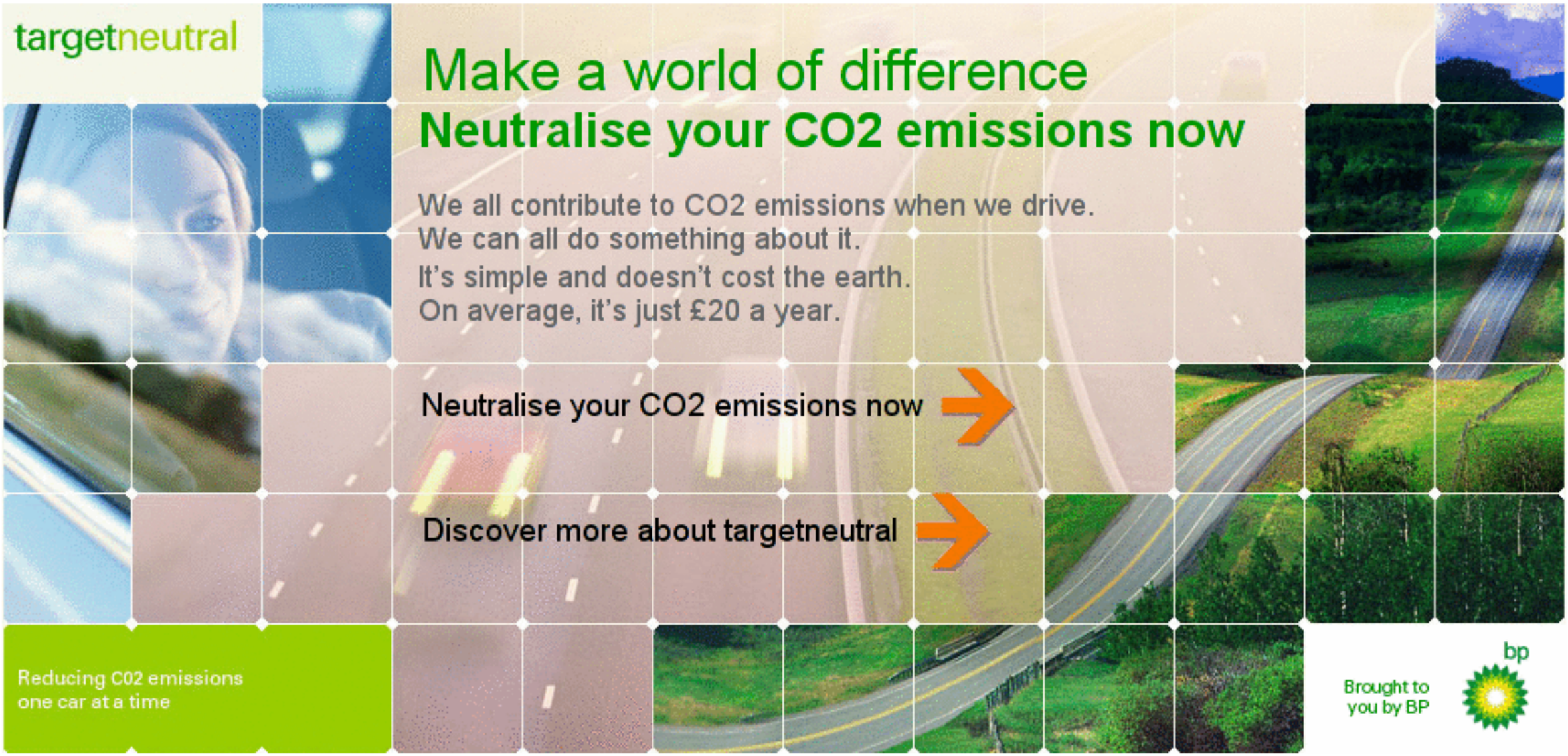


1880-2004

1f

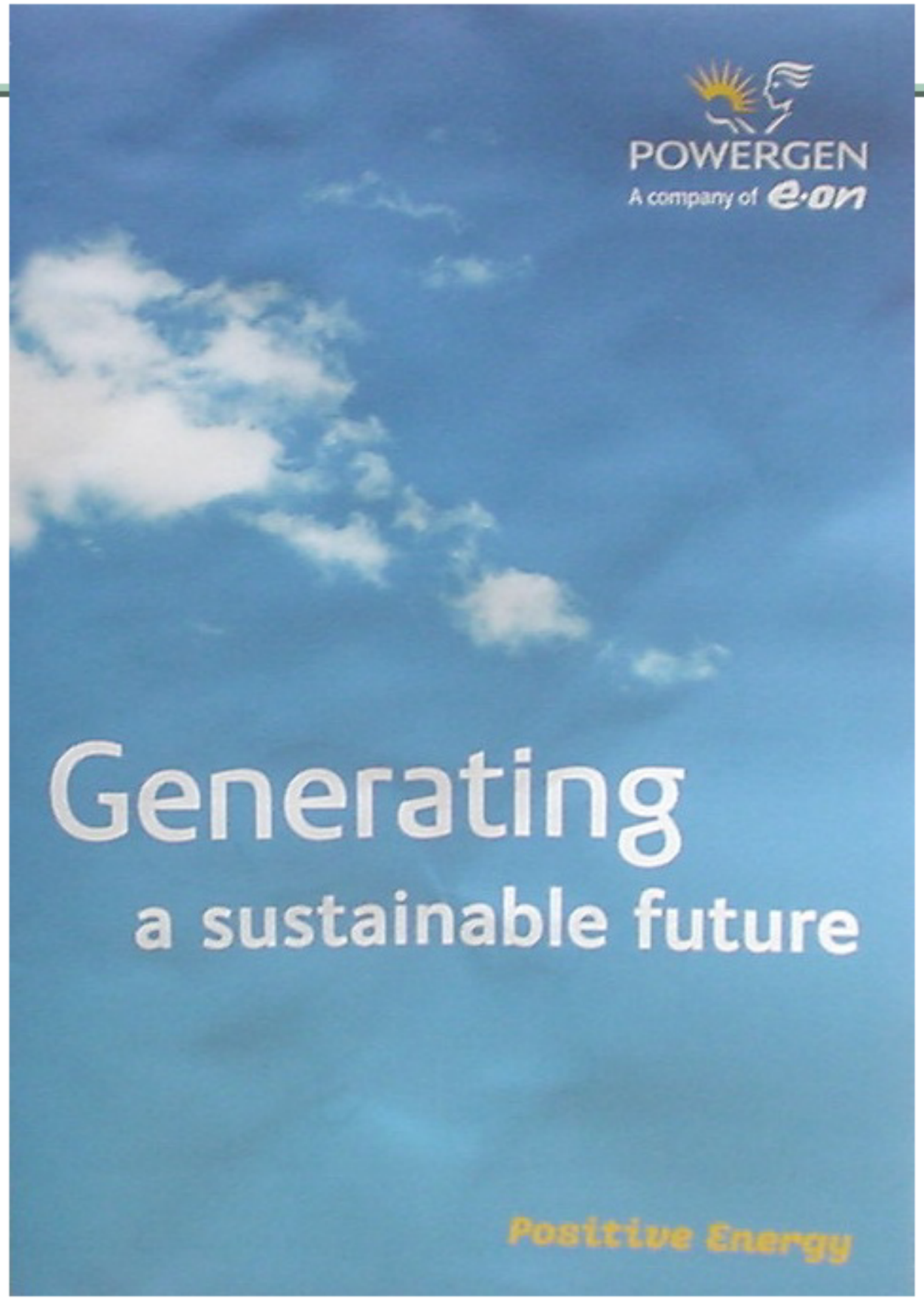
Something must be done!

'Make a difference'



'Do your bit' - Green tariffs

'Sustainable'



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

Biofuel

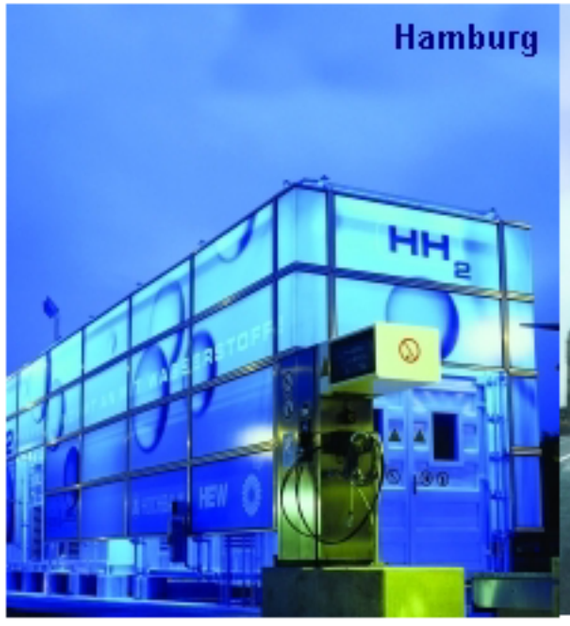
'Brown Takes Ride on Green Train'

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

A pump full of B5

Hydrogen

SUSTAINABLE
TRANSPORT
ENERGY



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**

34mpg

- **219g/km**

ything.

HEAD

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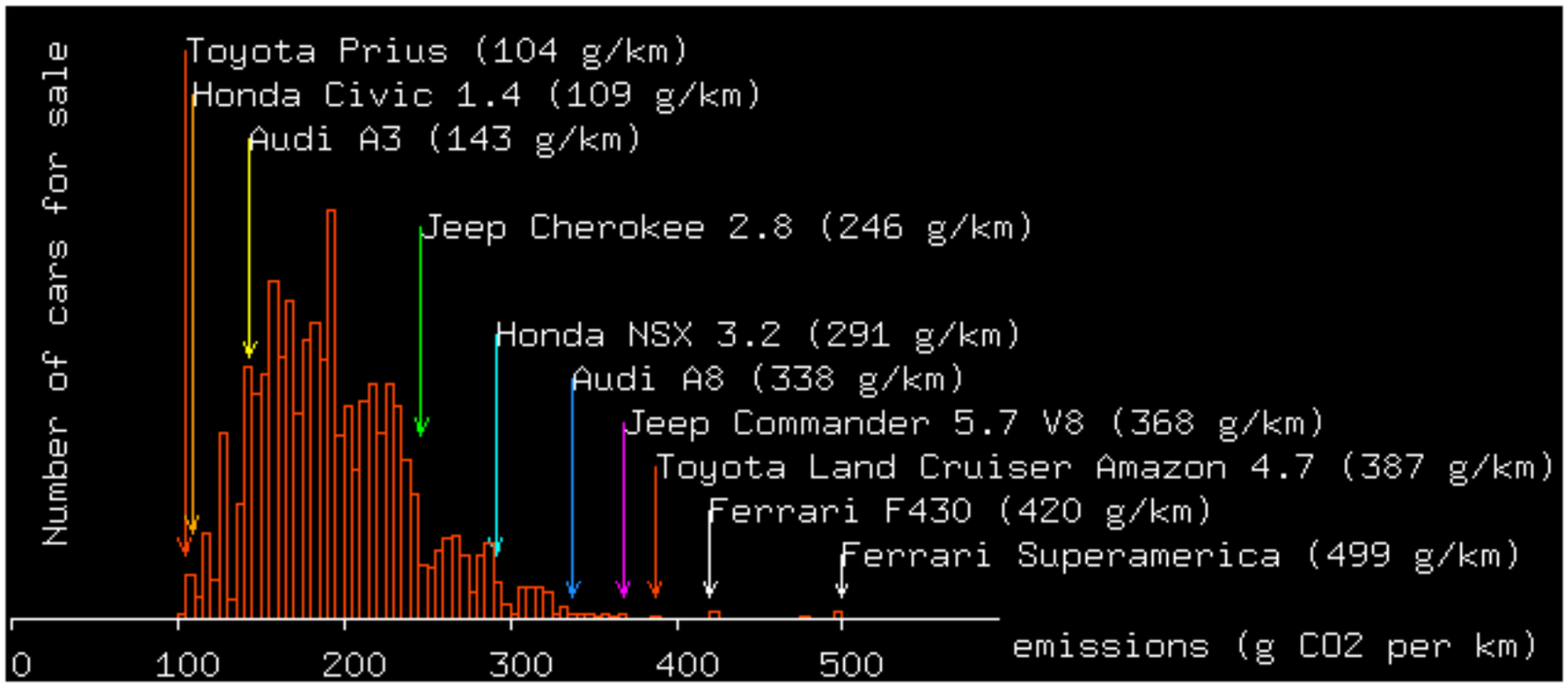
The 2.4 Diesel is efficient and probably the best all-round choice, offering 34mpg overall. During the past few years, it has

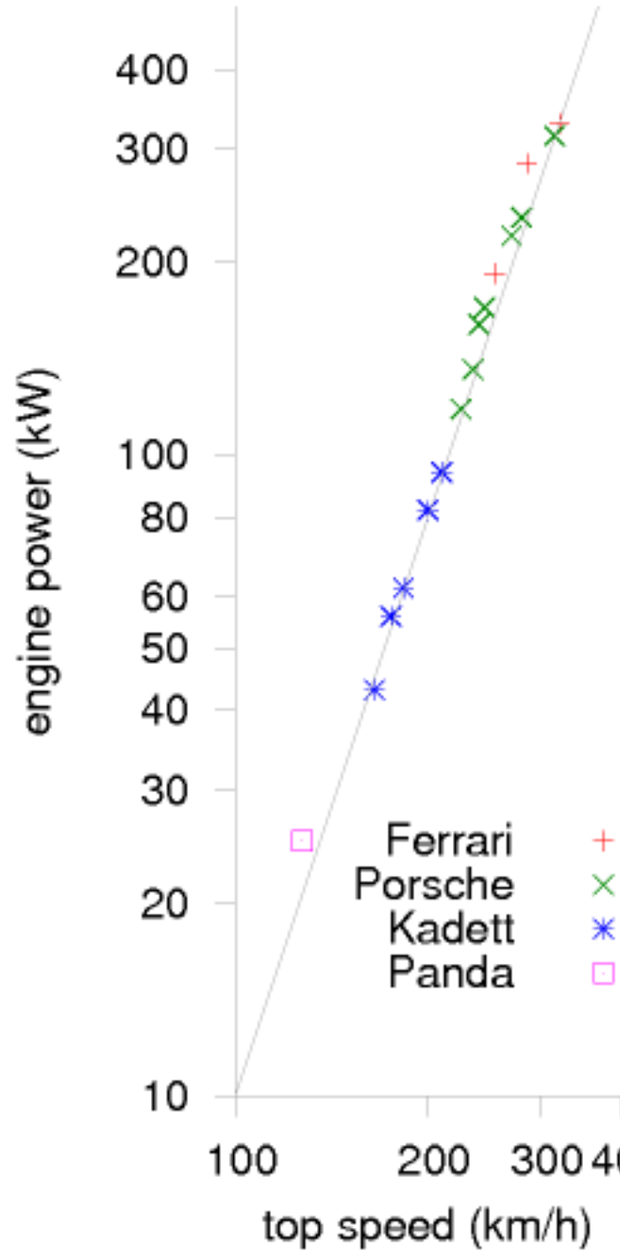
trouble is, the R-Class is furiously expensive, with prices starting at more than £38,000.

Practically perfect: the Volvo XC90

Carbon emissions from cars

Polo (102 g/km)





Something must be done!

Nuclear versus Wind

"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

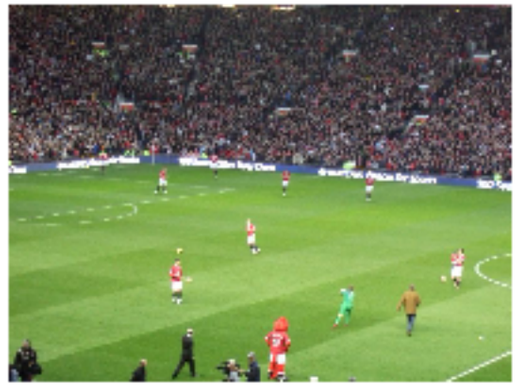
- Power unit: kWh per day

- Fluxes: W per square metre

- Examples
  - 20 mins of kettle - 1 kWh
  - food - 3 kWh / day(*)
  - bath - 5 kWh(*)
  - litre of petrol - 10 kWh
  - aluminium can - 0.6 kWh

- Population density: square metres per person

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



Drive a car 100km...

80 kWh

ything.

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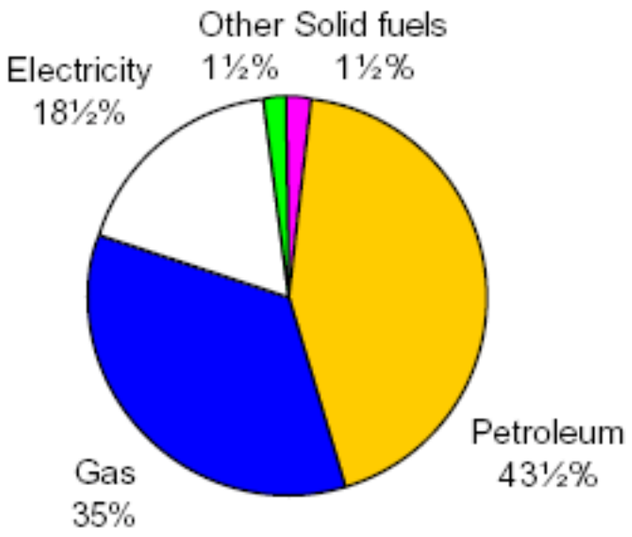
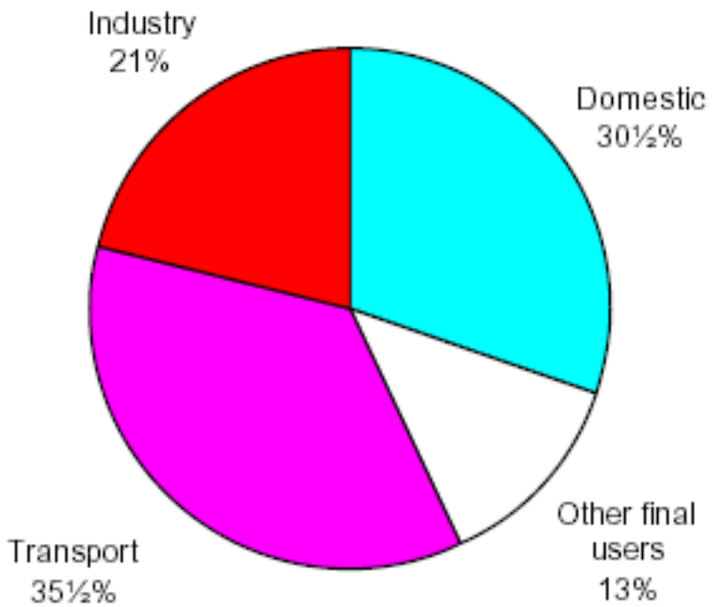
Practically perfect: the Volvo XC90

Average Power consumption, UK: 125 kWh/d each



2004



www.dti.gov.uk

125 kWh/day (Europe)

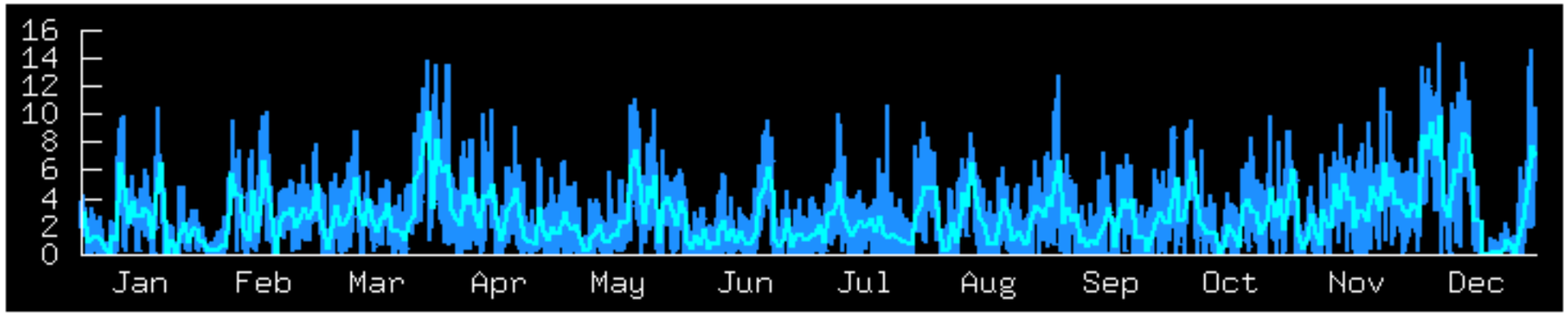
300 kWh/day (USA)

(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/year

Wind



Windspeeds Cambridge 2006 (m/s) Half-hourly and daily

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 country

- 400 square metres each

Wind: **20 kWh/d**

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

50 x Denmark's

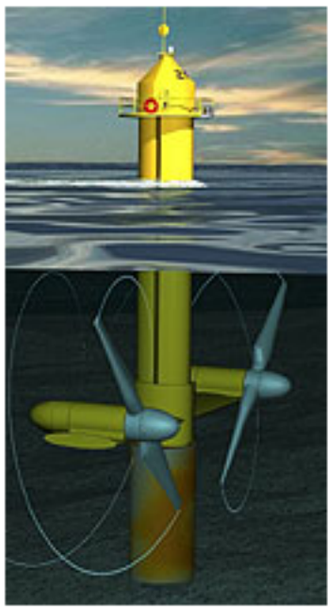
7 x Germany's

Renewables are diffuse

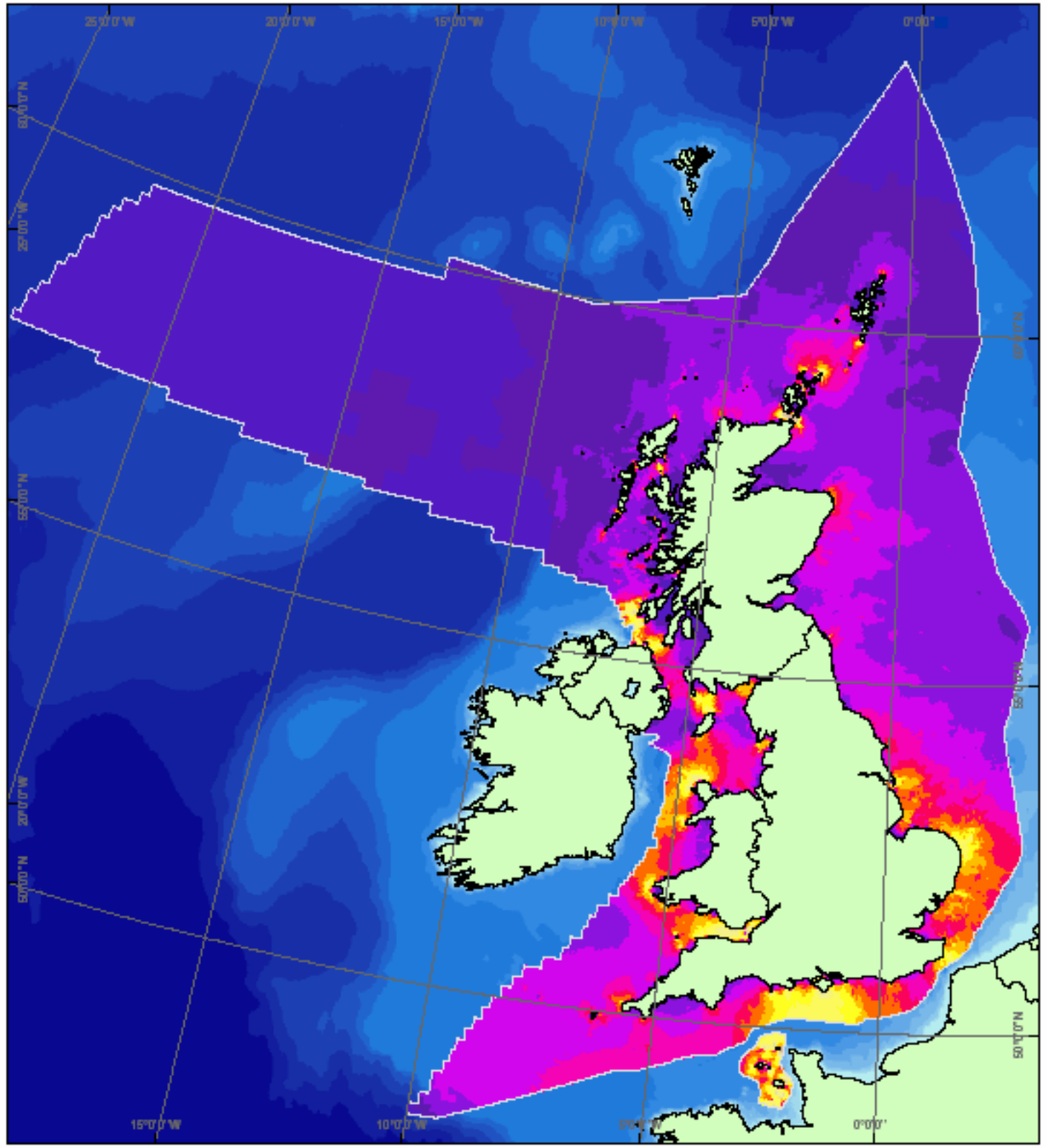
Power per unit land area	
Wind	$2\,\mathrm{W/m^2}$
Offshore wind	$3\,\mathrm{W/m^2}$
Tidal pools	$3\,\mathrm{W/m^2}$
Tidal stream	$6\,\mathrm{W/m^2}$
Solar PV panels	$5\,\mathrm{W/m^2}$
Plants	$0.5\,\mathrm{W/m^2}$
Solar chimney (Spain)	$0.1\,\mathrm{W/m^2}$
Concentrating solar power (desert)	$15\,\mathrm{W/m^2}$
Ocean thermal	$5\,\mathrm{W/m^2}$
Rain-water (Scotland)	$0.24\,\mathrm{W/m^2}$
Rain-water (England)	$0.02\,\mathrm{W/m^2}$

(c) Elsam (elsam.com).
Used with permission.

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



marineturbines.com



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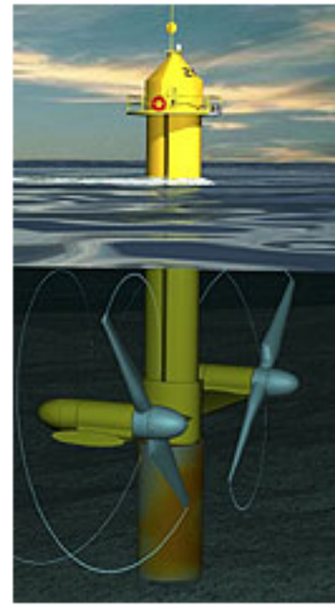

marineturbines.com

- 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 la
Wind	
Offshore wind	
Tidal pools	
Tidal stream	
Solar PV panels	
Plants	
Solar chimney (Spain)	
Concentrating solar power (des	
Ocean thermal	
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Nant-y-Moch by Dave Newbould
www.origins-photography.co.uk

- 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

Block

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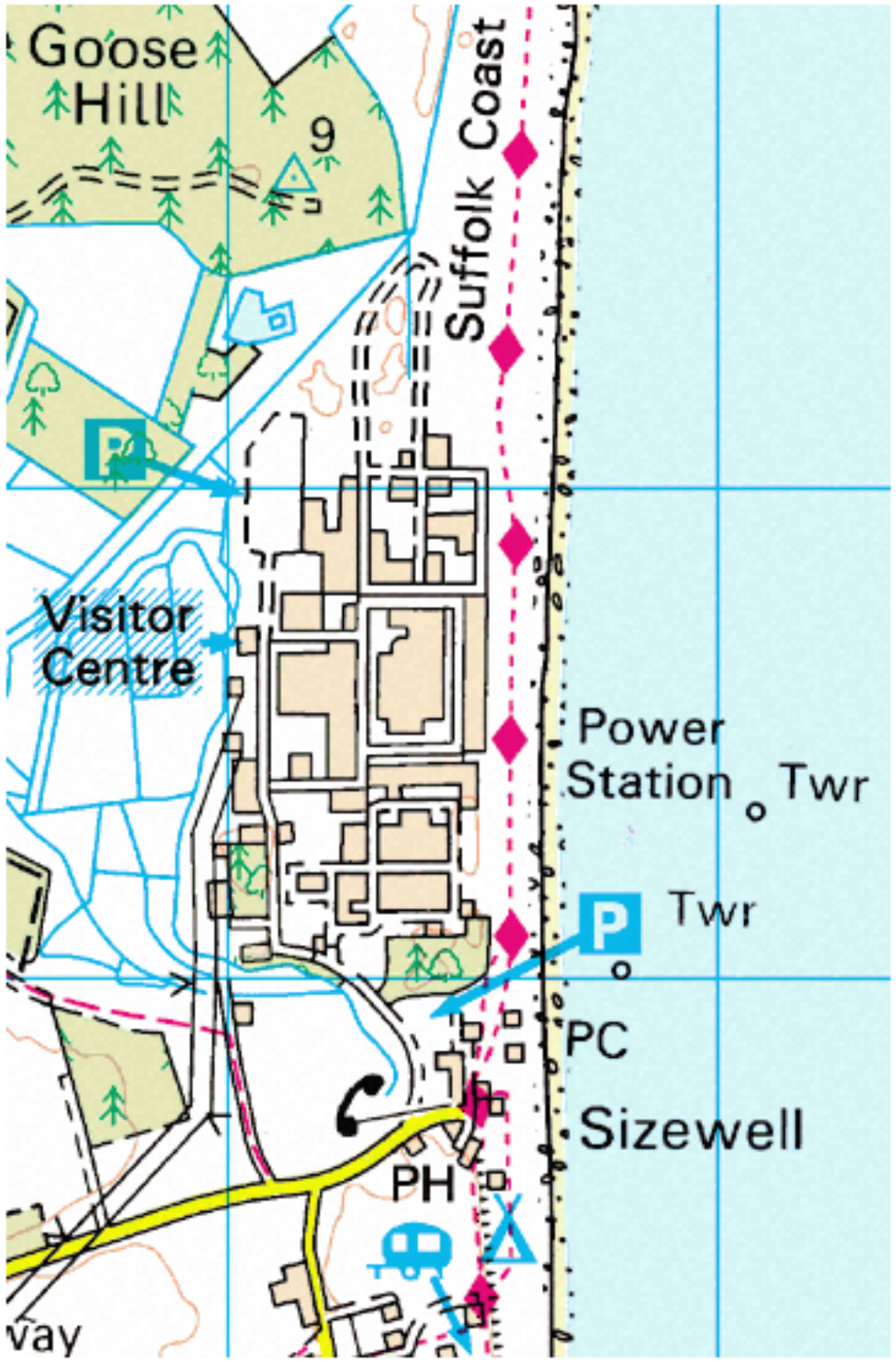
No green light for Severn barrage

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	$1000\,\mathrm{W/m^2}$

Current consumption: 125 kWh/d per person

We can't live on our own renewables

- at least, not as we currently live

Geothermal: **2**

Tide: **14 kWh/d**

Wave: **1.6**

Shallow offshore wind: **16 kWh/d**

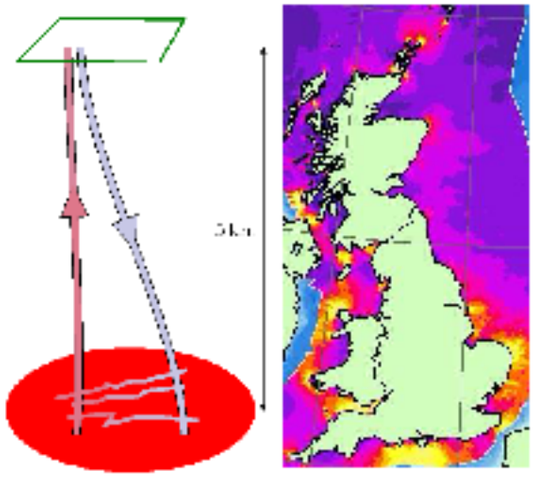
Hydro: **2**

Biomass: food, biofuel, wood, landfill gas: **24 kWh/d**

PV, 12 m^2: **5**

Solar heating (12 m^2): **12 kWh/d**

Wind: **20 kWh/d**



www.withouthotair.com

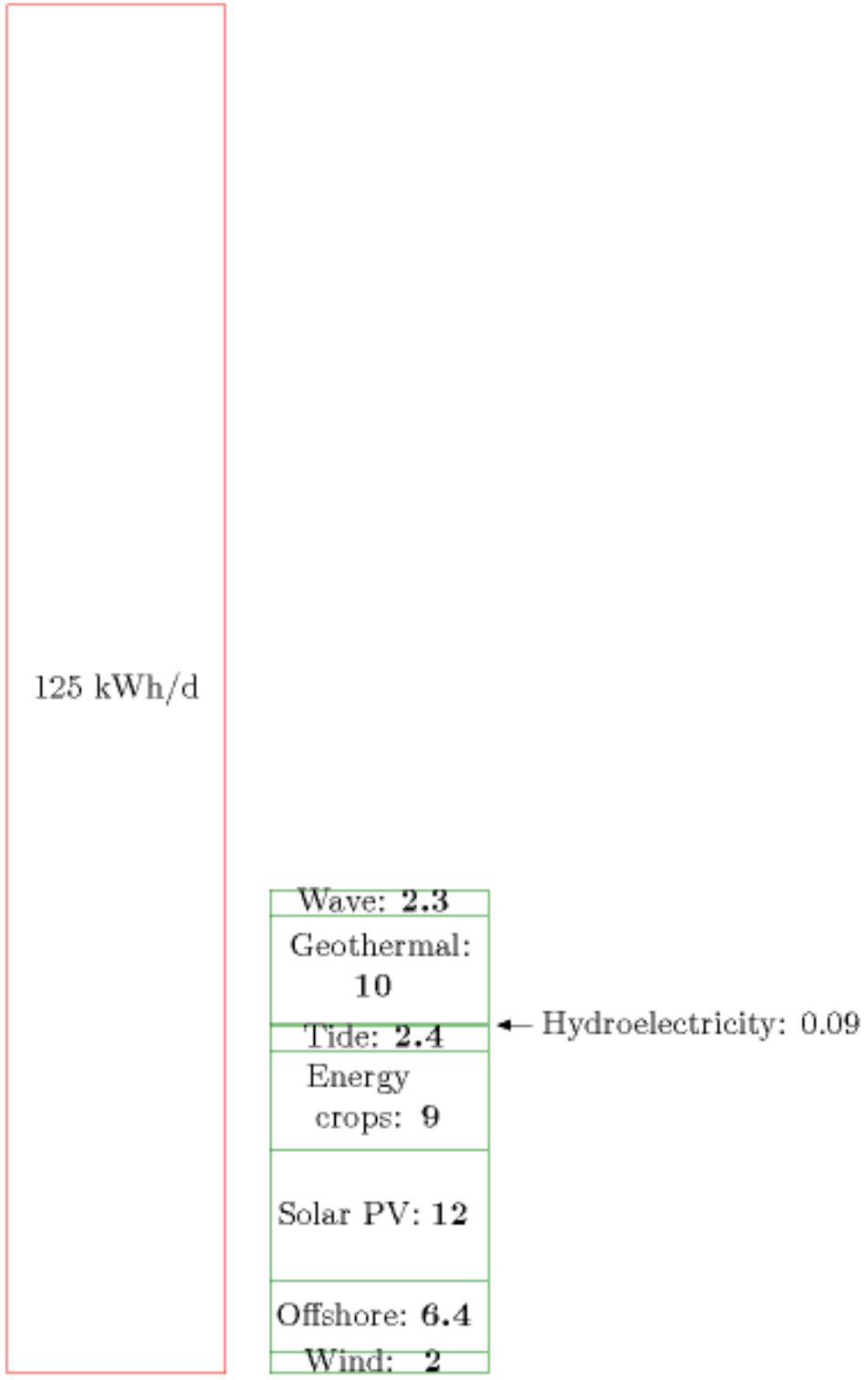
sustainable development commission

The role of nuclear power in a low carbon economy

Paper 2:
Reducing CO_2 emissions - nuclear and the alternatives

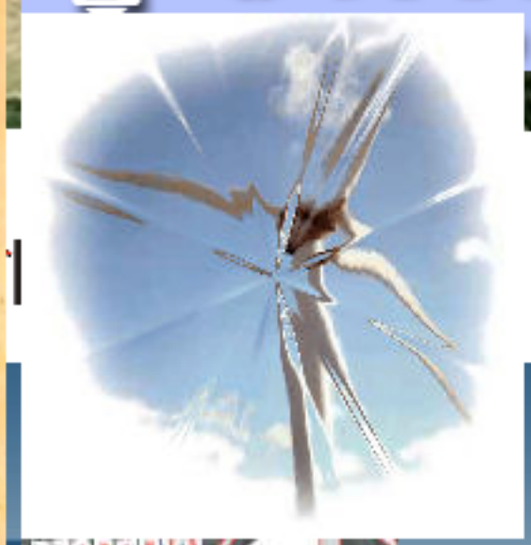
An evidence-based report by the Sustainable Development Commission

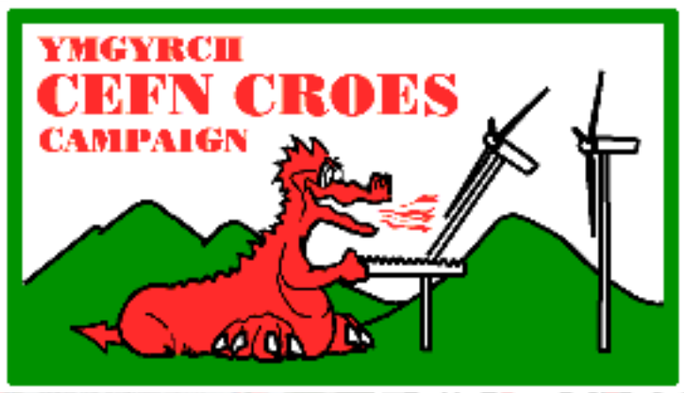
March 2006



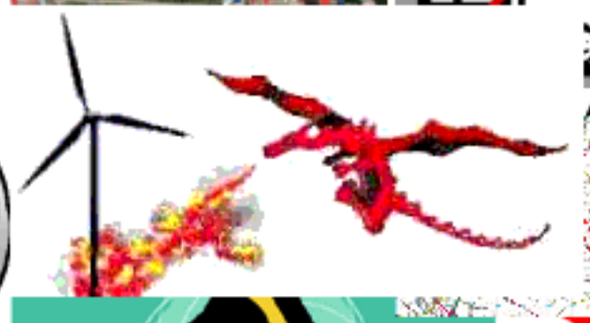
IEE's 'technical potential' is 'an upper limit that is unlikely ever to be exceeded even with quite dramatic changes in the structure of our society and economy'.

A consultation exercise in full swing

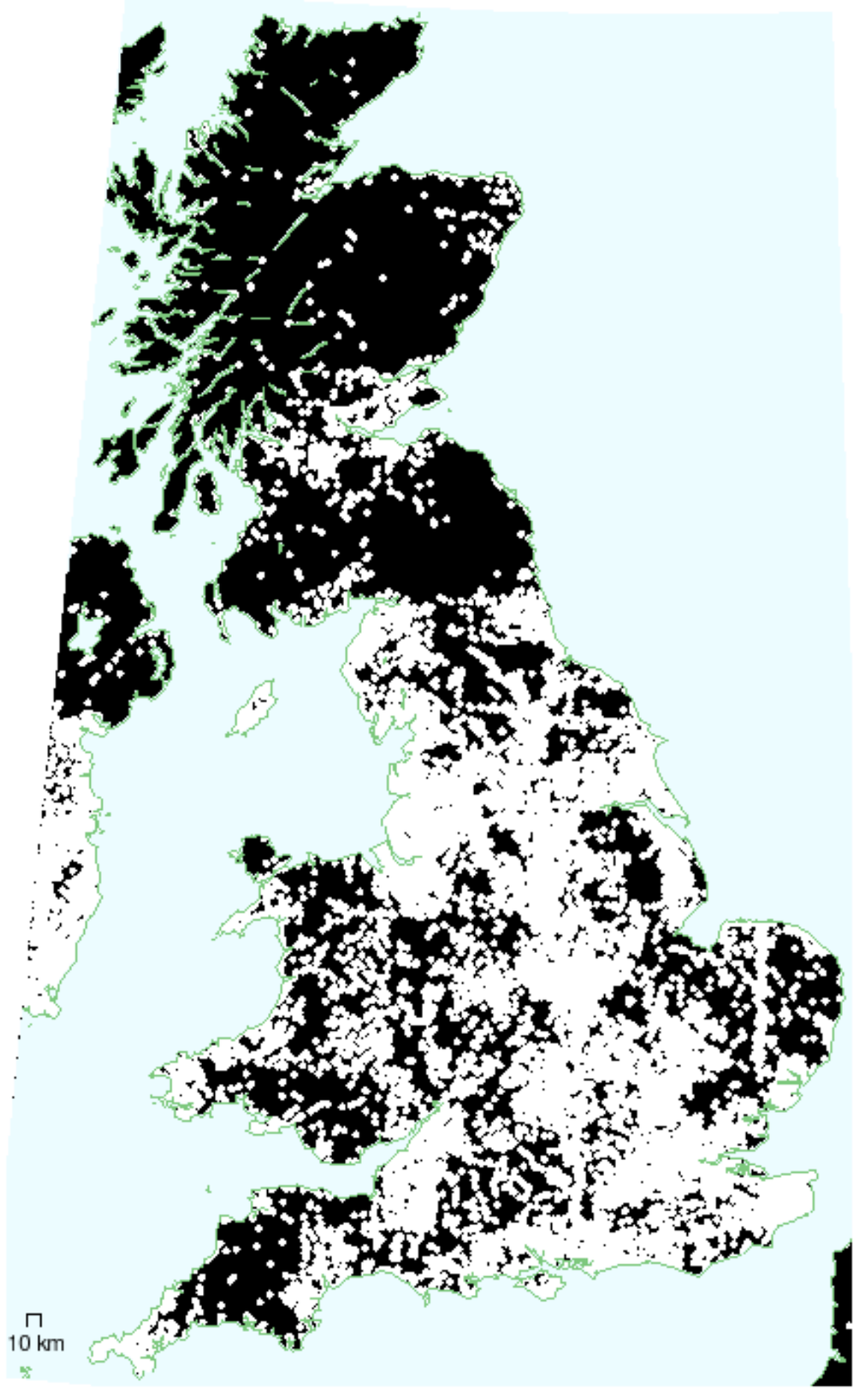




www.
stopbeningtonwindfarm
.co.uk



2km



Save Our Scenery -

Protecting Our Heritage Coastline

BEFORE

AFTER

FROM LLANDUDNO PROMENADE

FROM COLWYN BAY PROMENADE

saveourscenery.com

GRAVENEY RURAL ENVIRONMENTAL ACTION TEAM (GREAT)

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.

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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?"

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are springing up on land-based
some are even becoming tourist
– proposals for offshore farms are
popular.

Estate has
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ms in the
and off Portstewart, near the
seway in Northern Ireland.

Surfers are worried about the impact

About News Opinions Library Press

News

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 n experts say a wind farm next to the defunct nuclear power station, at Br air traffic control issues and might even interfere with radar. Airport mar Alistair Welch raised the concerns at a public inquiry which is being helc

June 22, 2007 in Echo

Southend Airport has raised serious objections to plans to build a new wind farm – even would be nearly 15 miles to the north.

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.

Protesters target wind farm plans

Plans of how the wind farm will look are on display

Porthcawl is a popular spot for surfers

Local people opposing plans to build one of the UK's big
south Wales coast met on Friday. Residents in Porthcaw
to highlight their opposition to the proposed 30-turbine
Sands.

SOS Porthcawl was set up by campaigners in the town v
say the wind farm will adversely affect the holiday reso
which attracts surfers and tourists from all over the UK
demonstration coincides with a public consultation into
project by developers United Utilities Green Energy.
Four-times British surf champion, Simon Tucker said the
was a lot of feeling against the proposals within the tow
"This demonstration is to ask the developers not to dest
the very environment they claim they are trying to prote
he said. Mr Tucker said the turbines, which are taller th
the Statue of Liberty in New York, will destroy the pano
views and also have an impact on the sea.

"The turbines will change the shape of the sandbanks a
the waves," he said. "If the waves are changed and peop
sport because of the turbines then the town is going to
company behind the £100m scheme say the turbines, wh
sea level, will generate enough power for 86,000 homes
The site, which is to the west of Porthcawl, is approxima
the nearest household.

Project - Is This A New Klondyke?

y Herald (linked above) talks about the views
and disappearing as we used to know them - vast
st as they had been for hundreds of years and
n industrial scene. As we watch the first massive
aithness and Sutherland coast are we watching
other aspect of our scenery - the coastal views?
another hazard for fishing boats and vessels to
view now of anyone on the east of Caithness are
thers as we face up to rising oil prices and the
. We already see oil rigs with in view. Will wind
ut at sea than on our hills and mountains?

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Fishermen oppose wind farm plans

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

Hundreds of turbines could be built about five miles off the coast

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'

Andy Roper, who organised the protest, emphasised the fishermen's livelihoods are being threatened.

From The Times

November 23, 2002

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

EXPLORE UK NEWS

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From The Times

February 4, 2008

Wind farms 'a threat to national security'

Magnus Linklater and Dominic Kennedy

Ambitious plans to meet up to a third of Britain's energy needs from offshore wind farms are in jeopardy because the Ministry of Defence objects that the turbines interfere with its radar.

The MoD has lodged last-minute objections to at least four onshore wind farms in the line of sight of its stations on the east coast because they make it impossible to spot aircraft, *The Times* has learnt. The same objections are likely to apply to wind turbines in the North Sea, part of the massive renewable energy project announced by John Hutton, the Energy Secretary, barely two months ago. They would be directly in line with the three principal radar defence stations, Brizlee Wood, Saxton Wold and Trimingham on the Northumberland, Yorkshire and Norfolk coasts.

Wind power 'a security ris

02 November 2007 08:15

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

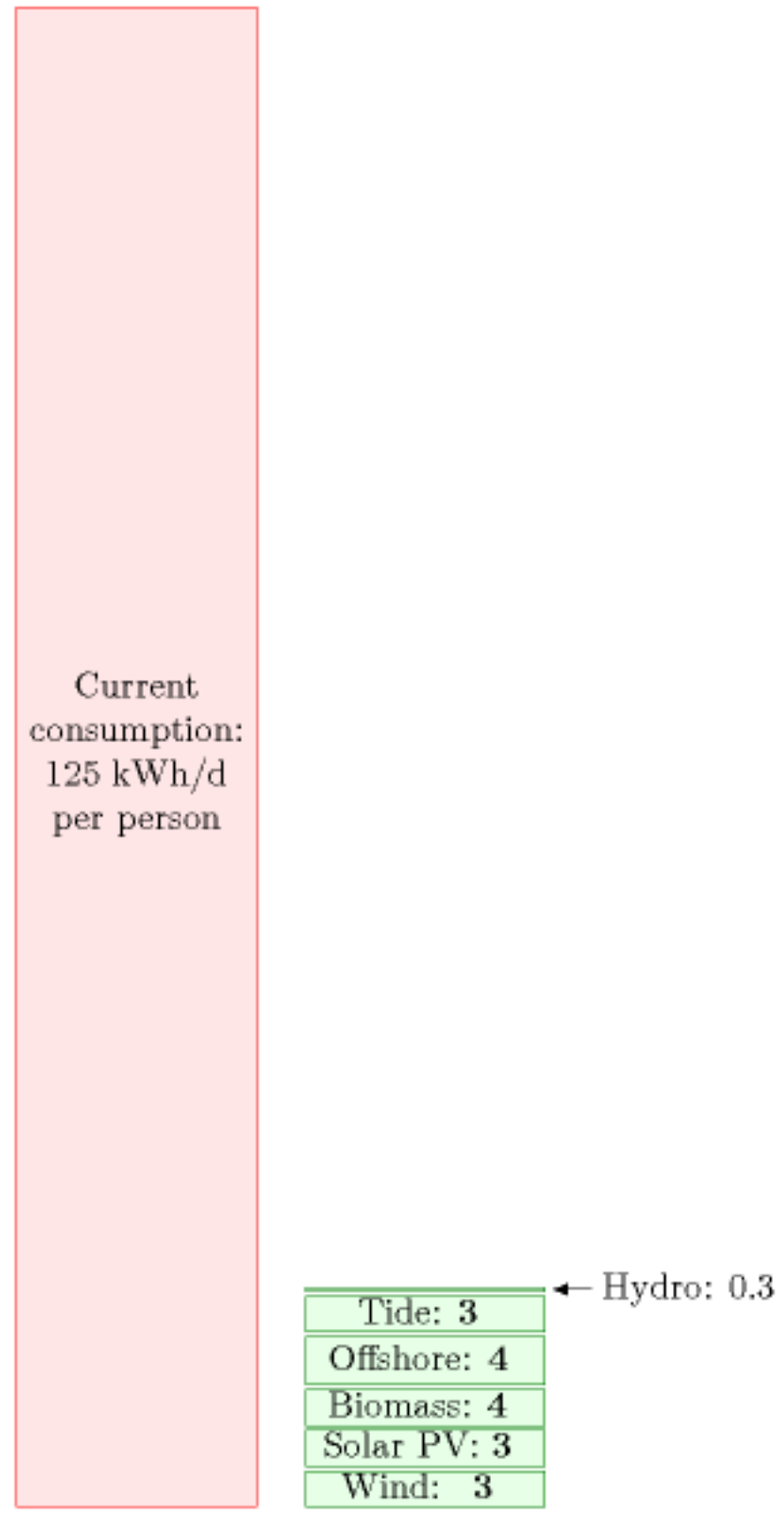
Experts say the MoD now objects to abou 50pc of applications to build onshore wir turbines because of concerns they affect performance of military radar.

GREEN CENTRAL BLOG

Guilt-free flying? Are biofuels the future for aviation?

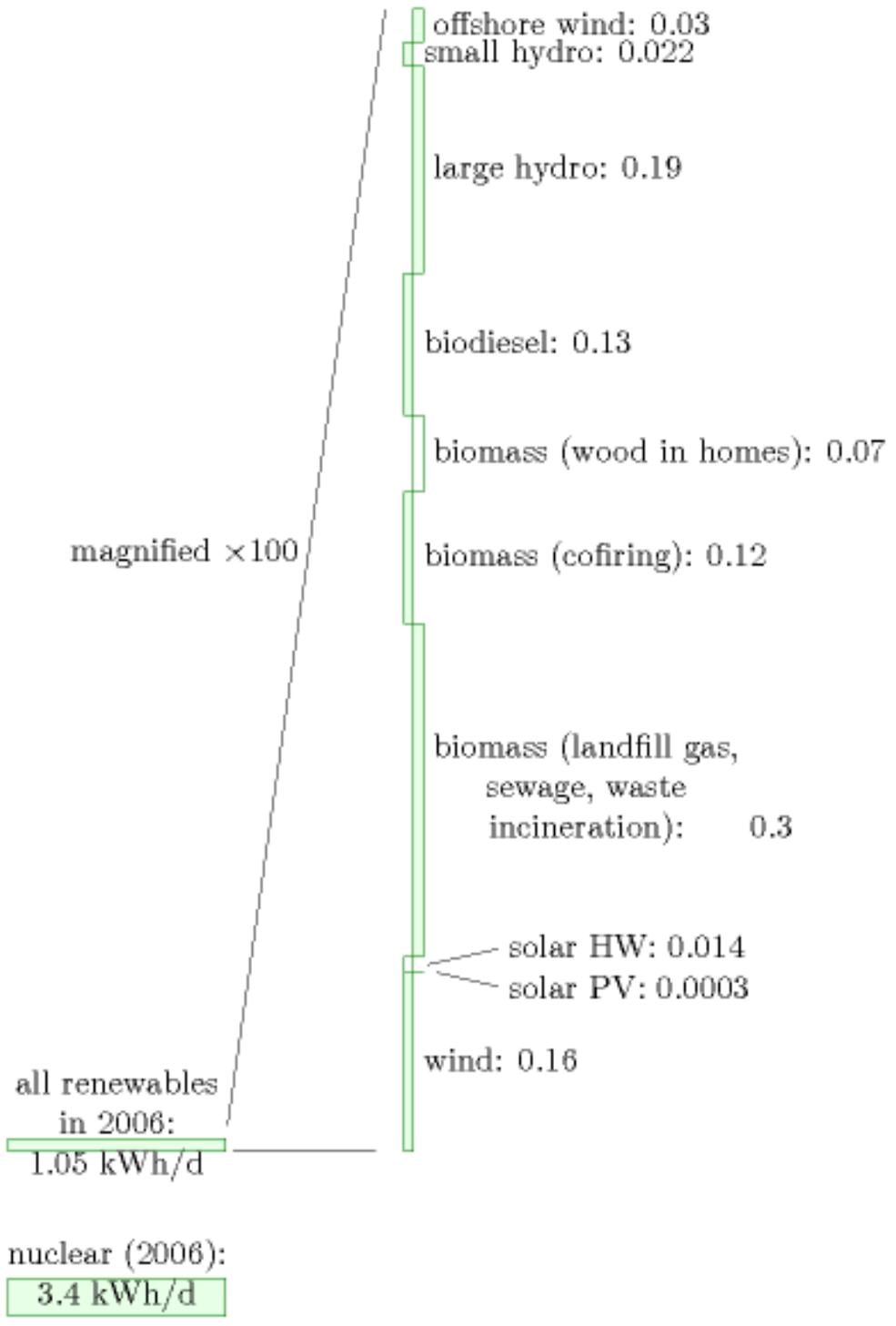
20 green ideas for Valentines day

after the great British consultation exercise...



This would be a 15-fold increase of renewables

Today's supply of renewables



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

1 per sq km
43 per sq km
1000 per sq km

Area / km^2

1e+08
1e+07
1e+06
100000
10000
1000

10000
100000
1e+06
1e+07
1e+08
1e+09

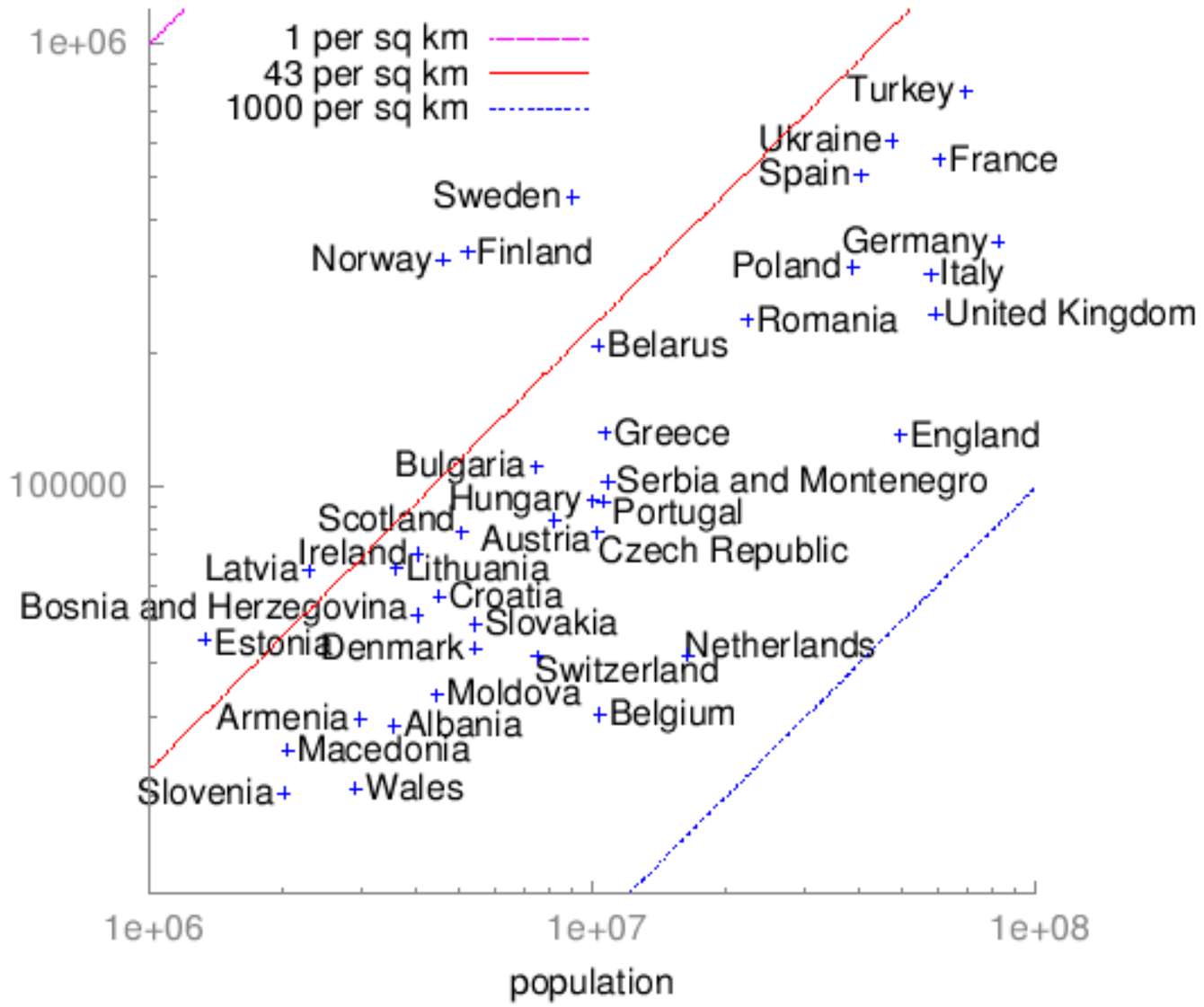
Population

World
Asia
Africa
North America
Latin America
Europe
Antarctica
Canada
Australia
India
Kazakhstan
Greenland
Libya
Alaska
Mongolia
Mauritania
Namibia
Botswana
Western Sahara
Gabon
Guyana
Suriname
Iceland
French Guiana
Bangladesh
England
South Korea
Scotland
Taiwan
Wales
Mauritius
Hong Kong
Singapore
Gaza Strip

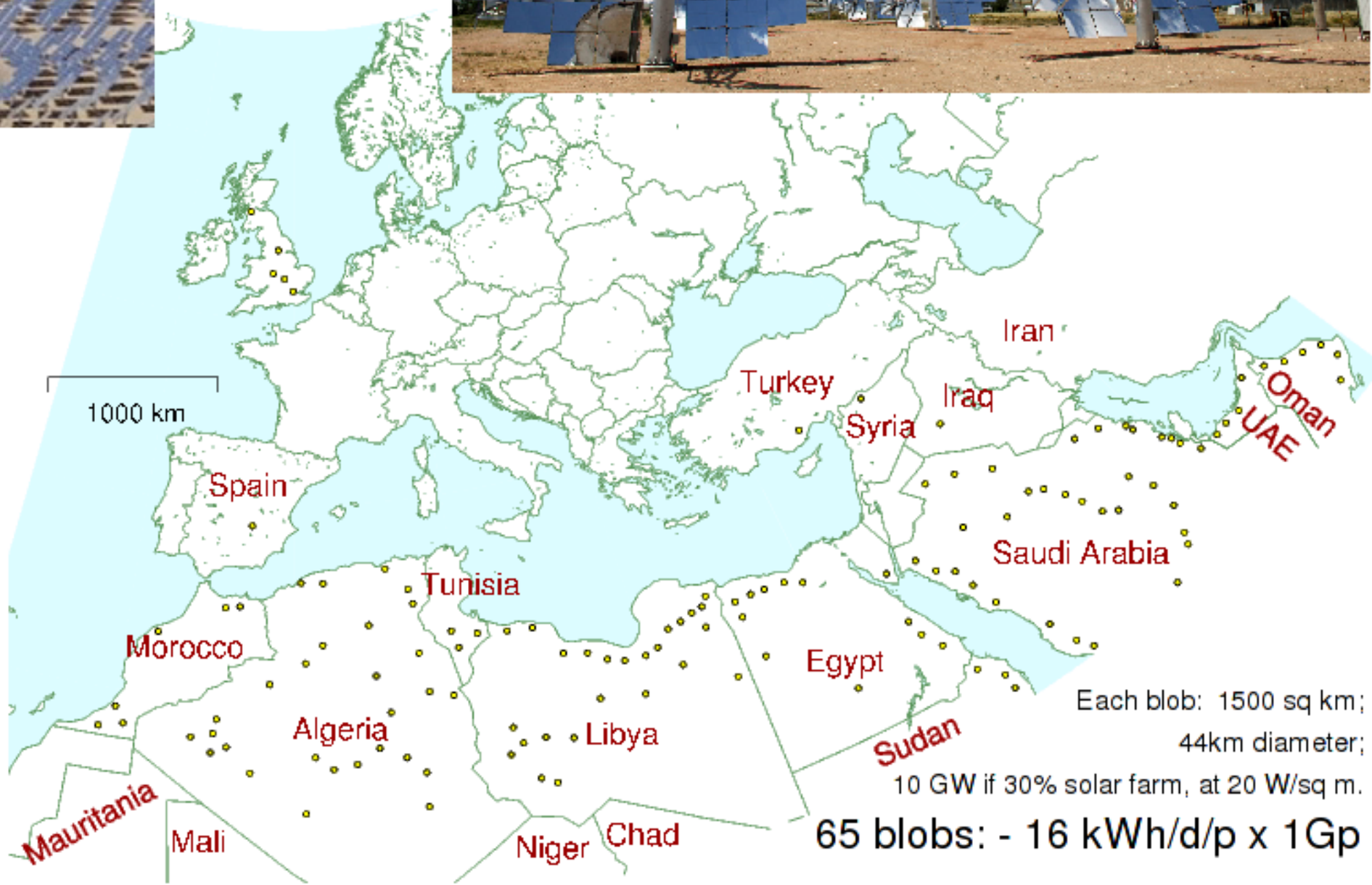
23 000 m^2 per person

1000 m^2 per person

Population densities in Europe



International renewables



Spain

1000 km

Morocco

Tunisia

Algeria

Libya

Mauritania

Mali

Niger

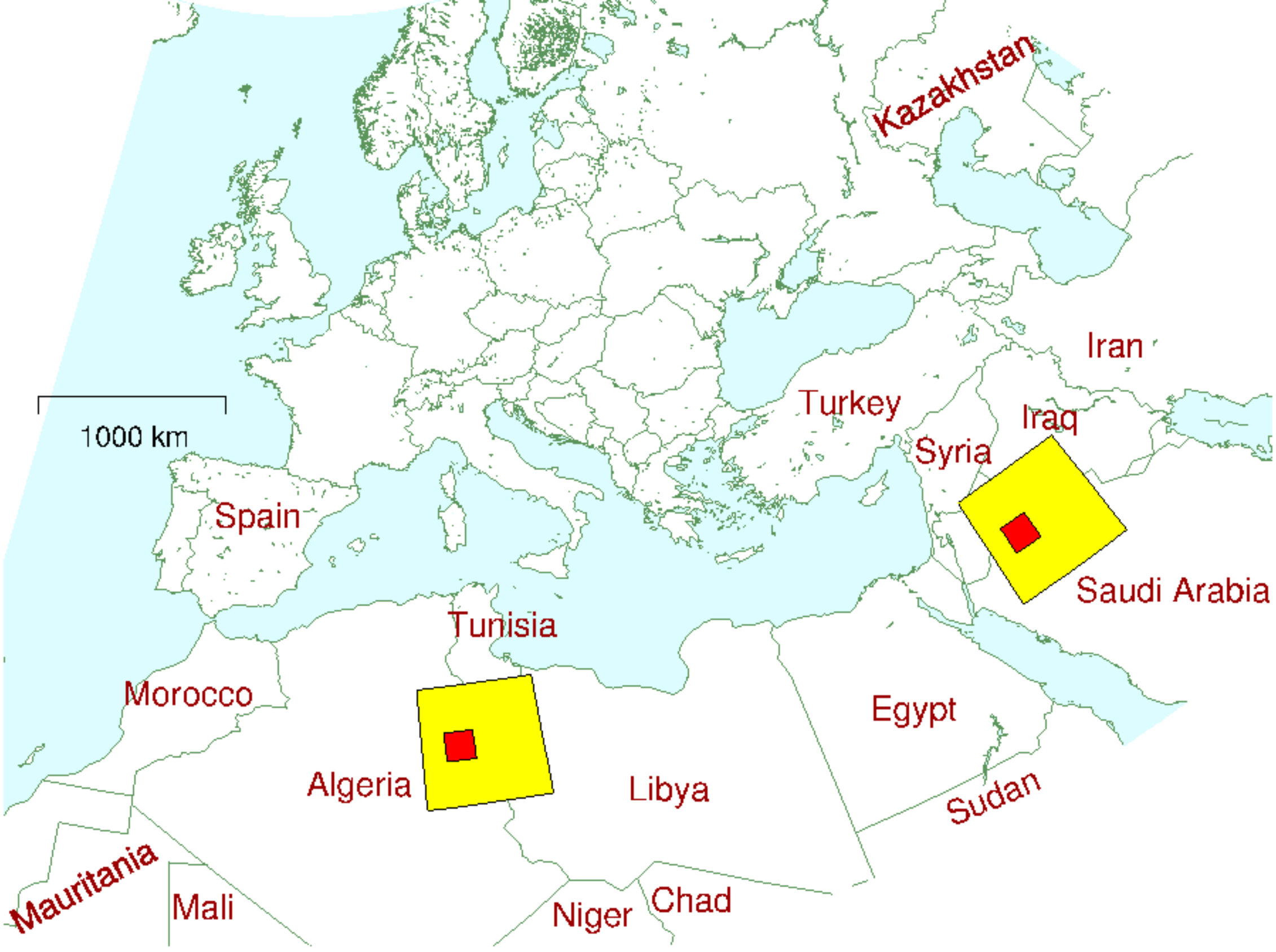
Chad

Each blob: 1500 sq km;

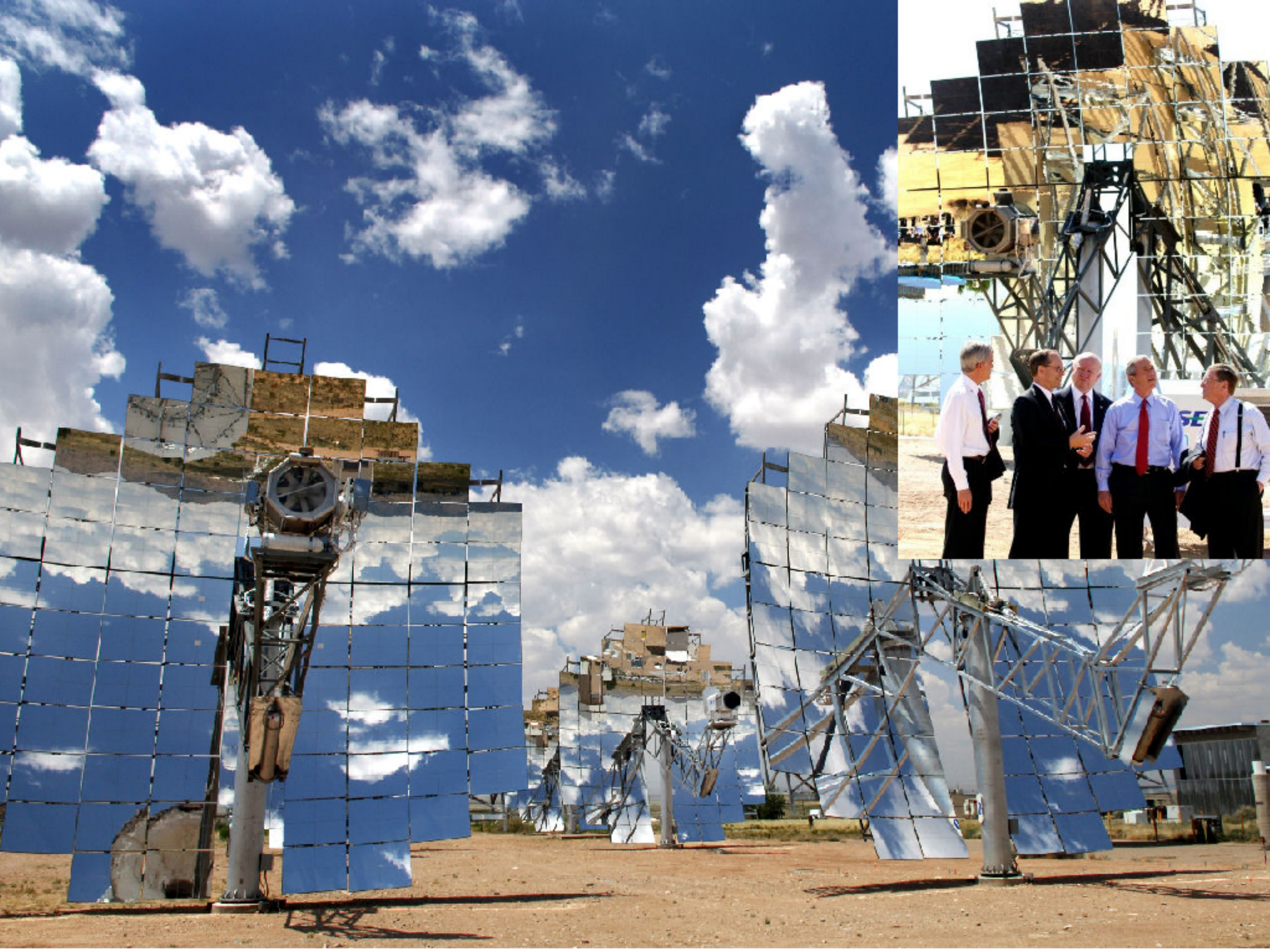
44km diameter;

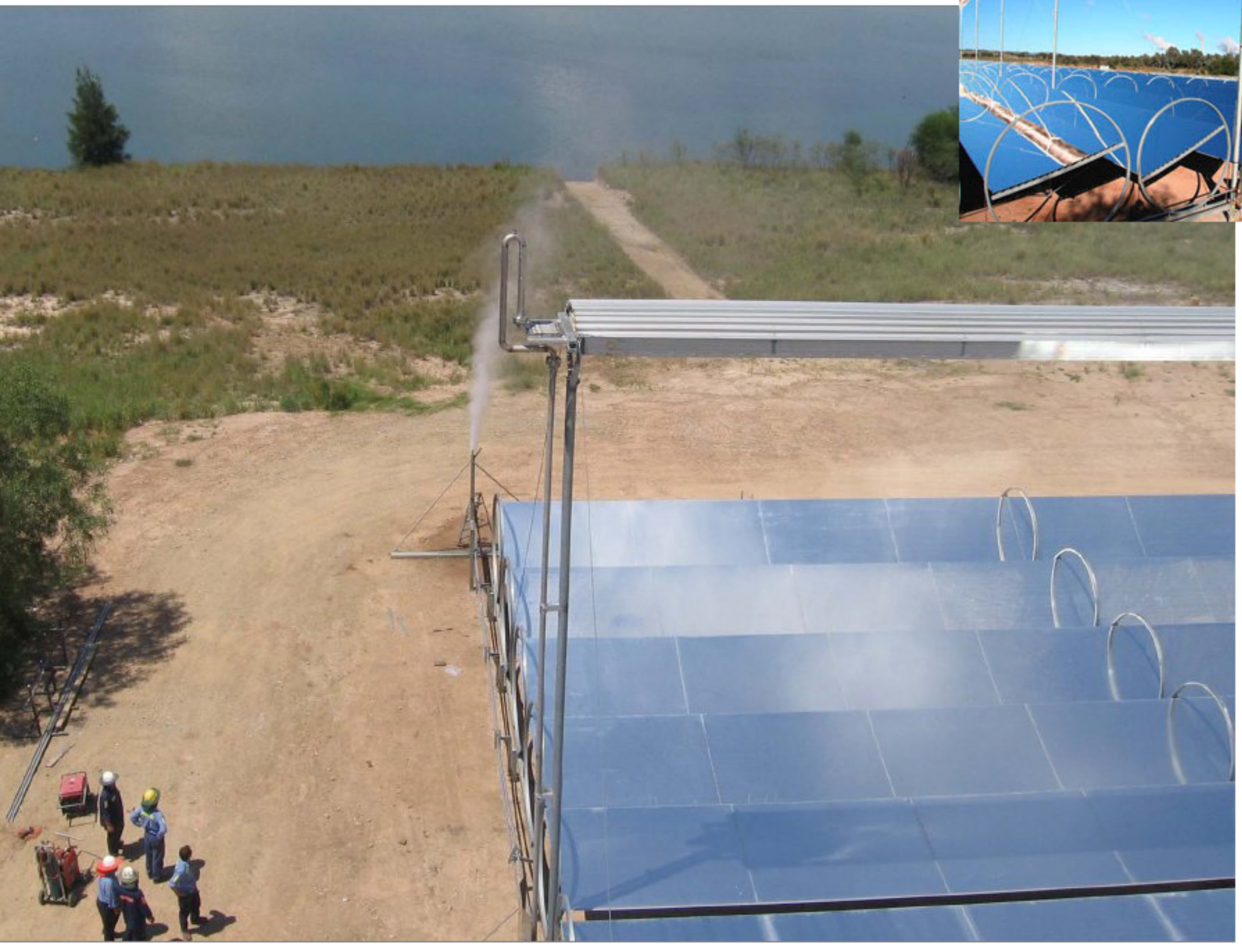
10 GW if 30% solar farm, at 20 W/sq m.

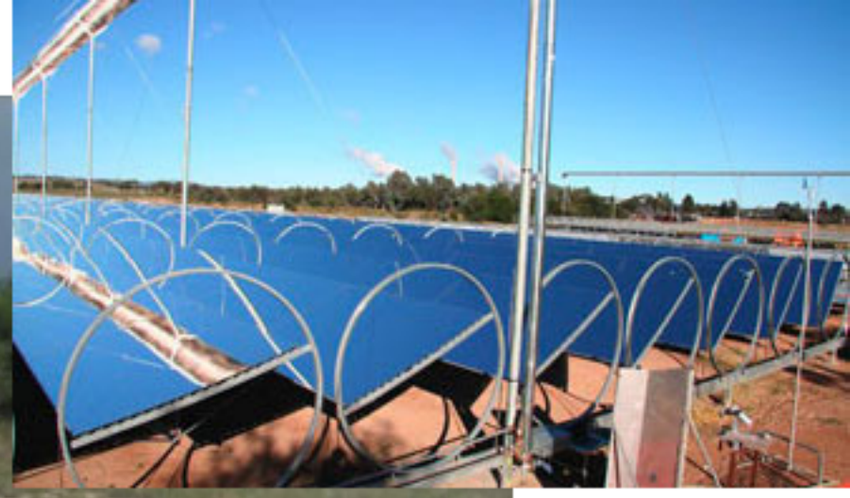
65 blobs: - 16 kWh/d/p x 1Gp



Yellow: 125 kWh/d/p for 1 billion people; Red: 125 kWh/d/p for 60 million people





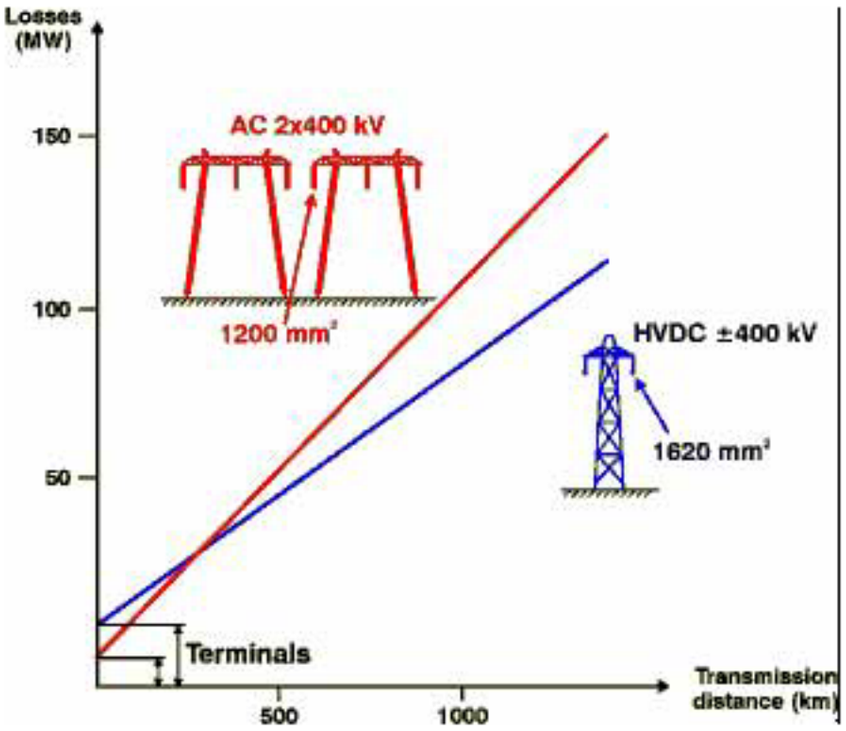


ausra.com

Andasol, Spain

$10\ \mathrm{W/m^2}$

HVDC transmission



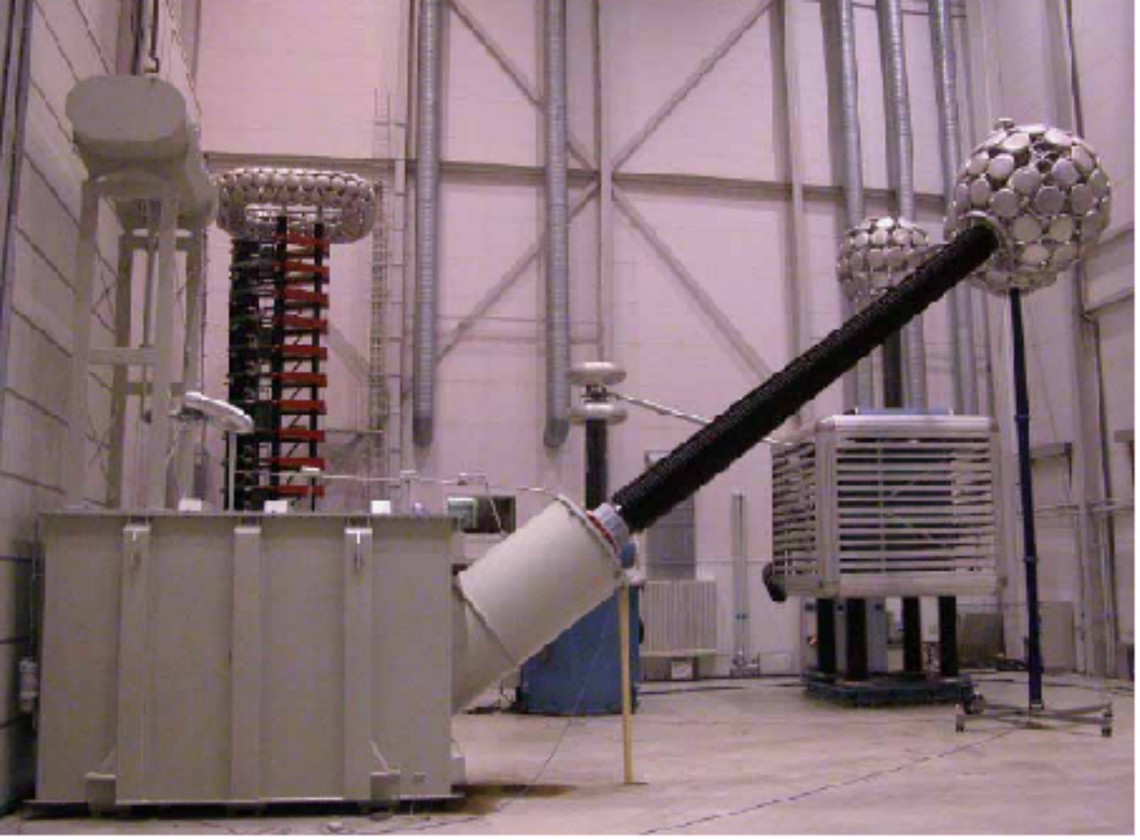
Photos and diagrams: ABB

2GW -->

3.1GW, 1360km

1.9GW, 1420km

0.7GW, 580km



Photos: ABB

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

Efficiency

- 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.

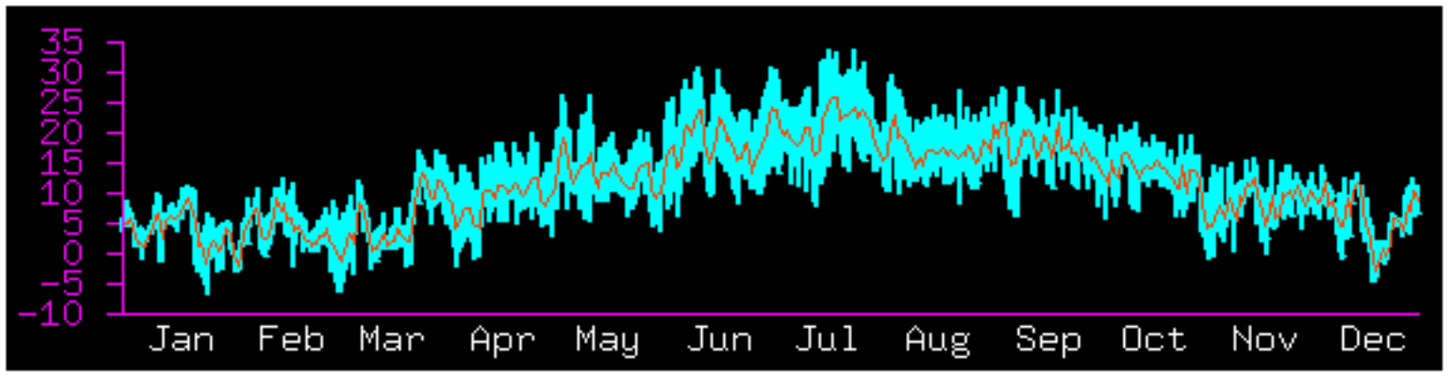
Efficiency II

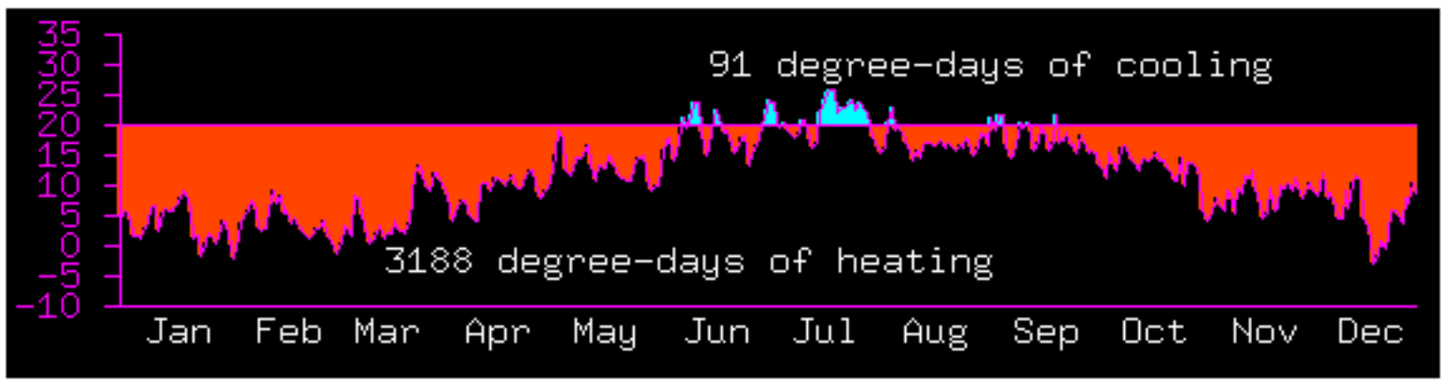
- Heating

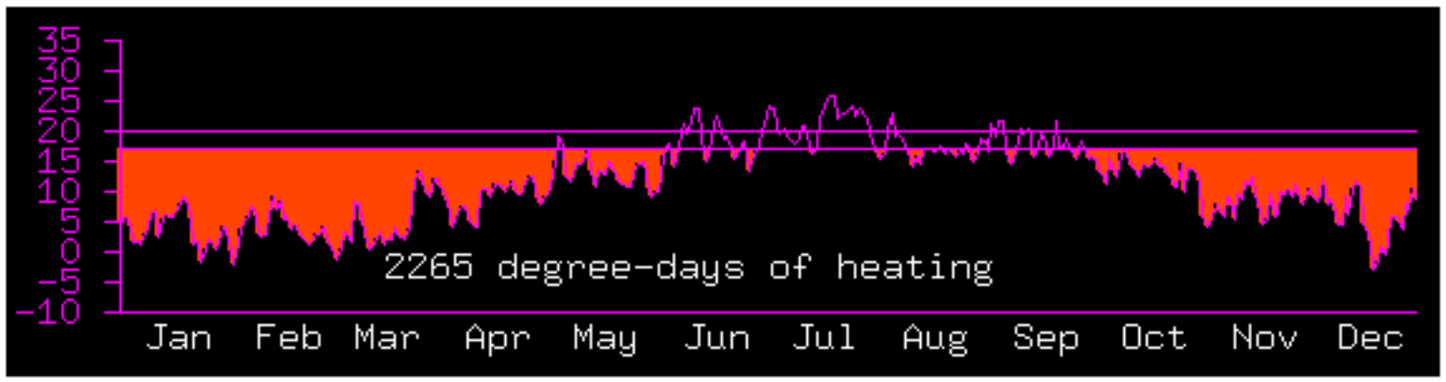
$$\underset{\text{(kWh/d)}}{\text{Heat loss}} = \underset{\text{(kWh/d/°C)}}{\text{Leakiness}} \times \underset{\text{(°C)}}{\text{Average temperature difference}}$$

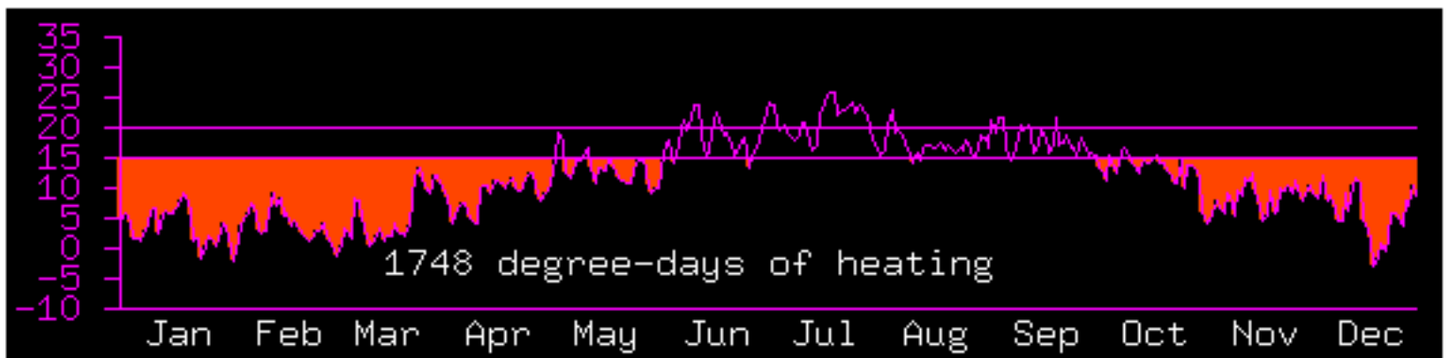
Turn the thermostat down

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

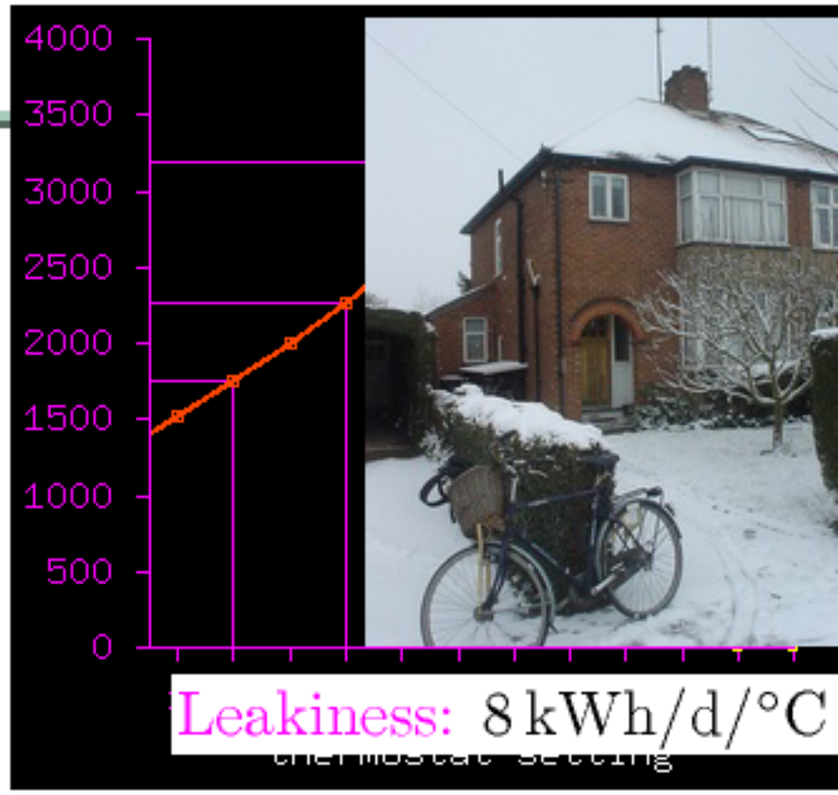




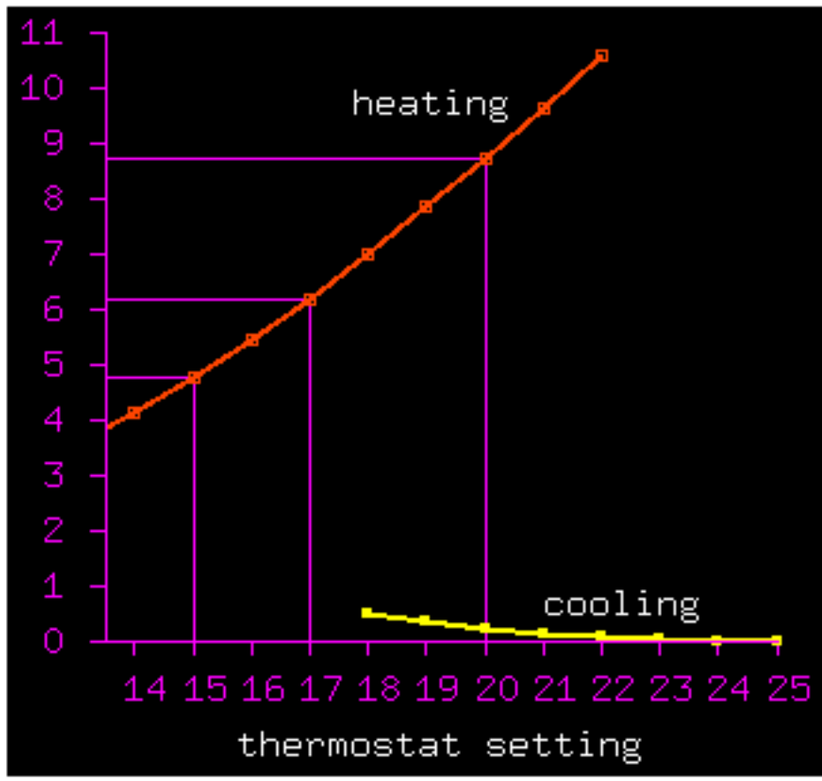




Temperature demand, in degree-days per year



Average temperature difference

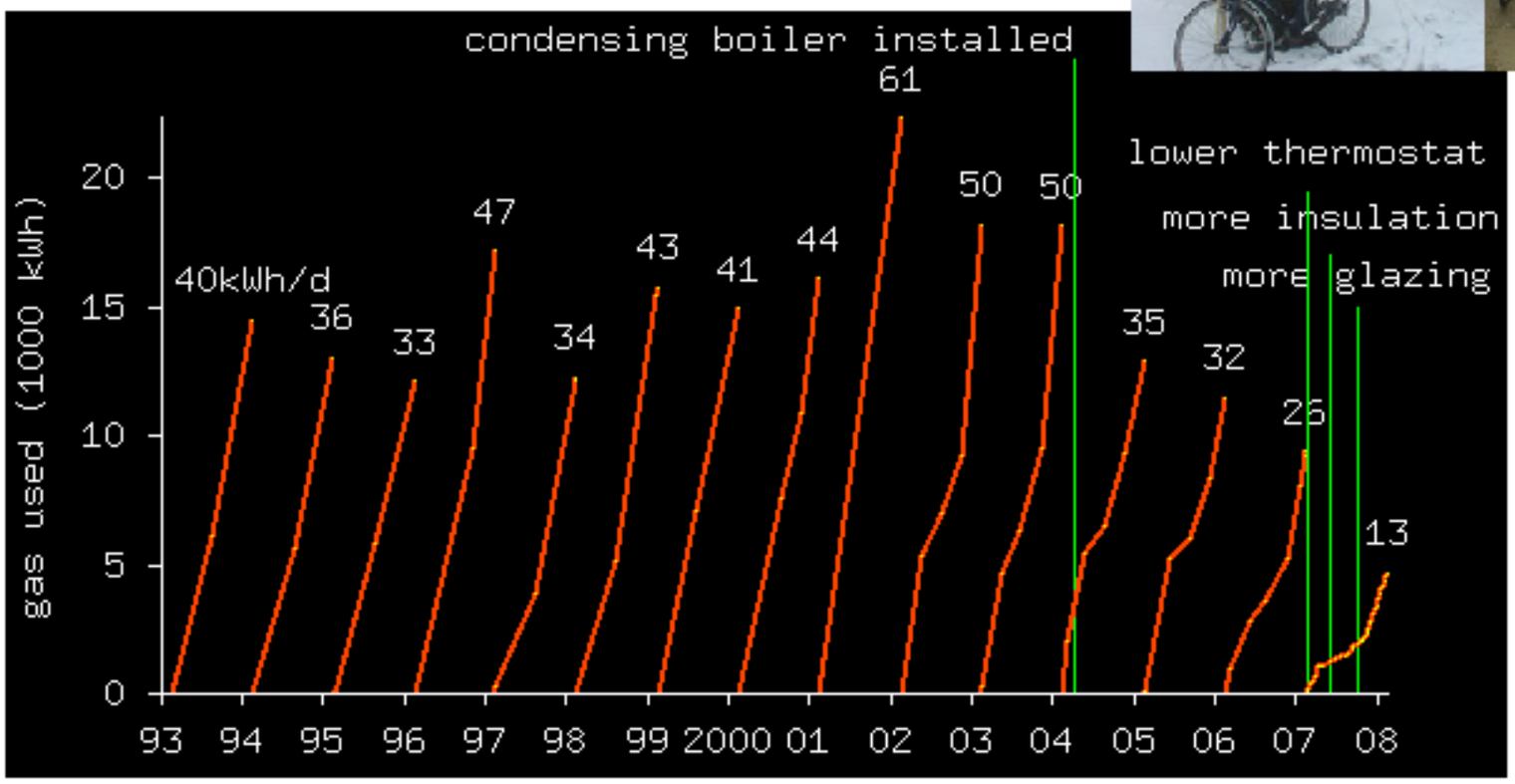


Reduce leakiness

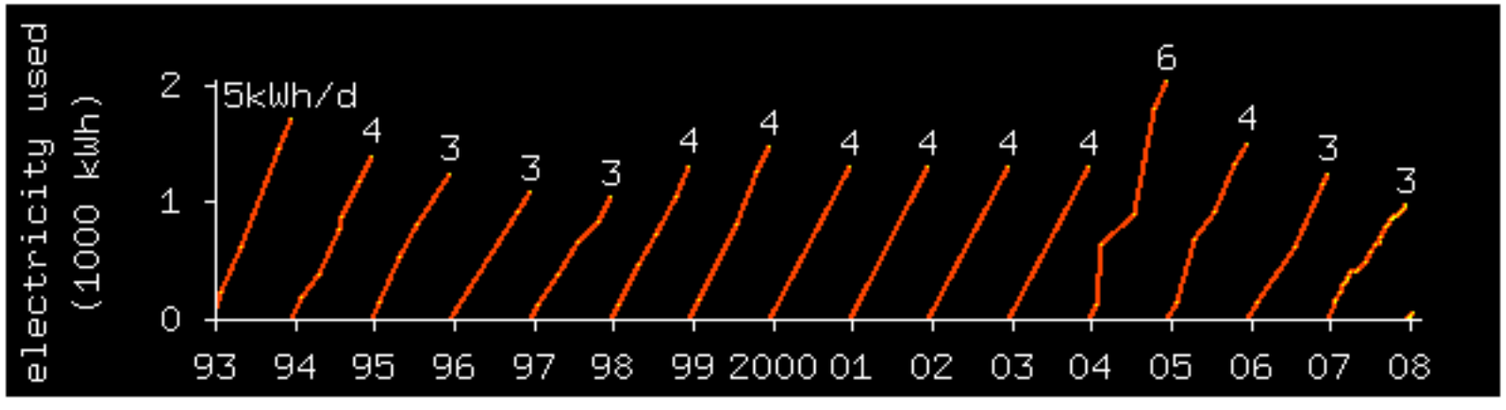
New leakiness: 6 kWh/d/°C

Read your meters!

- Gas

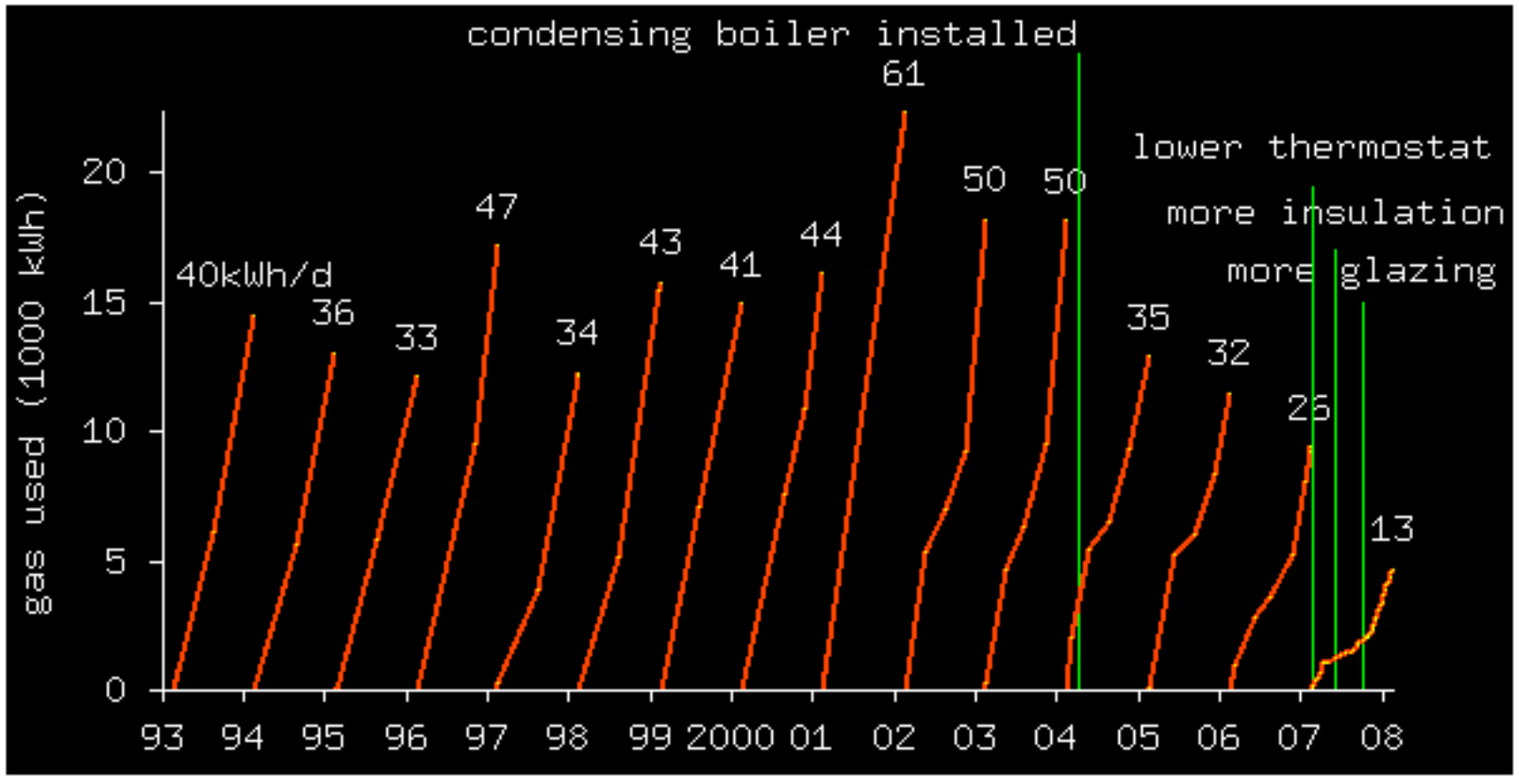


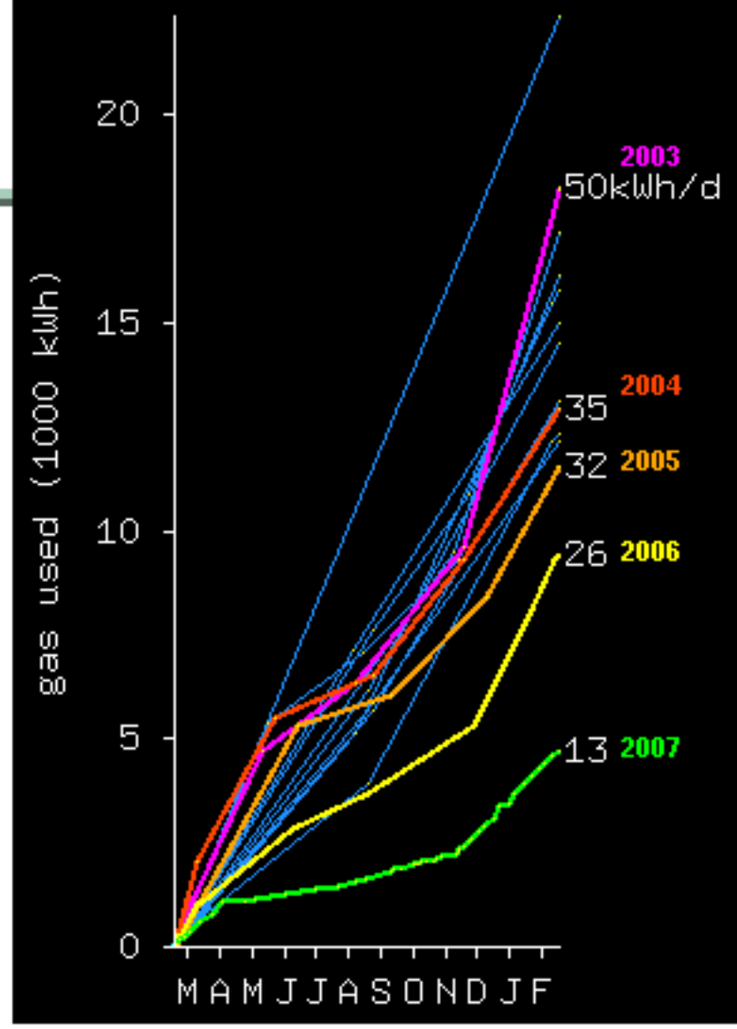
- Electricity



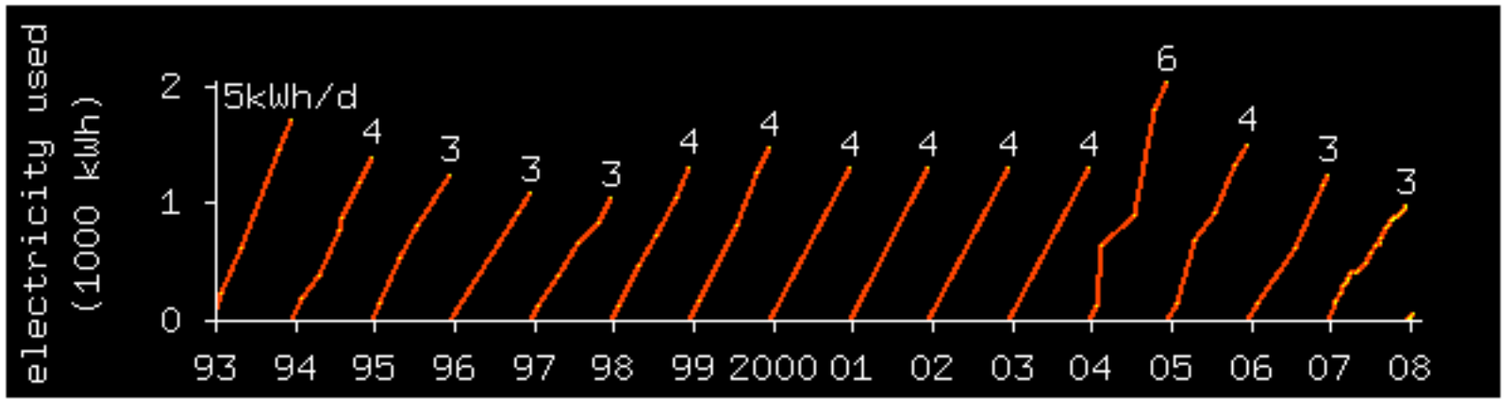
Read your meters!

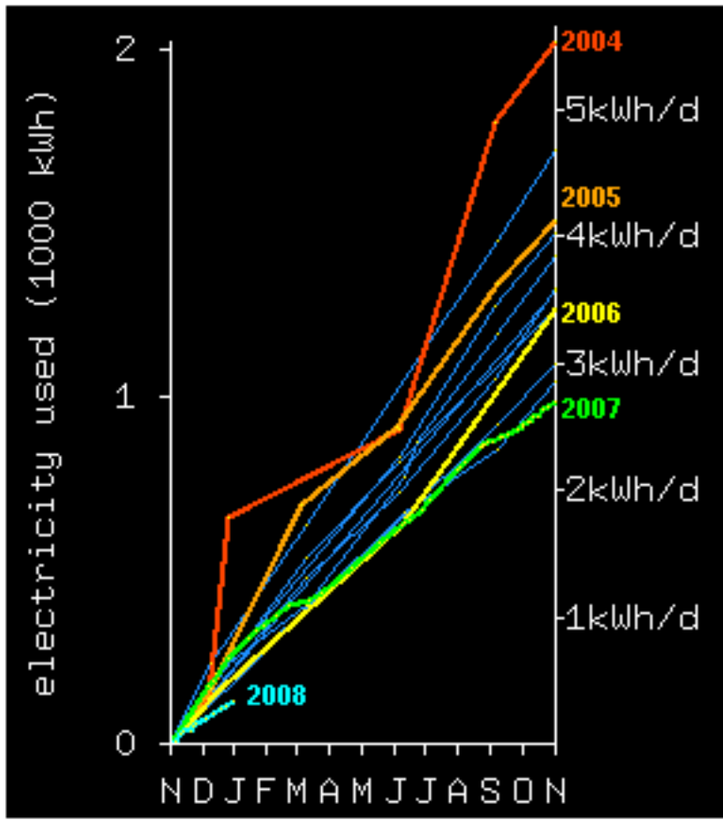
Gas





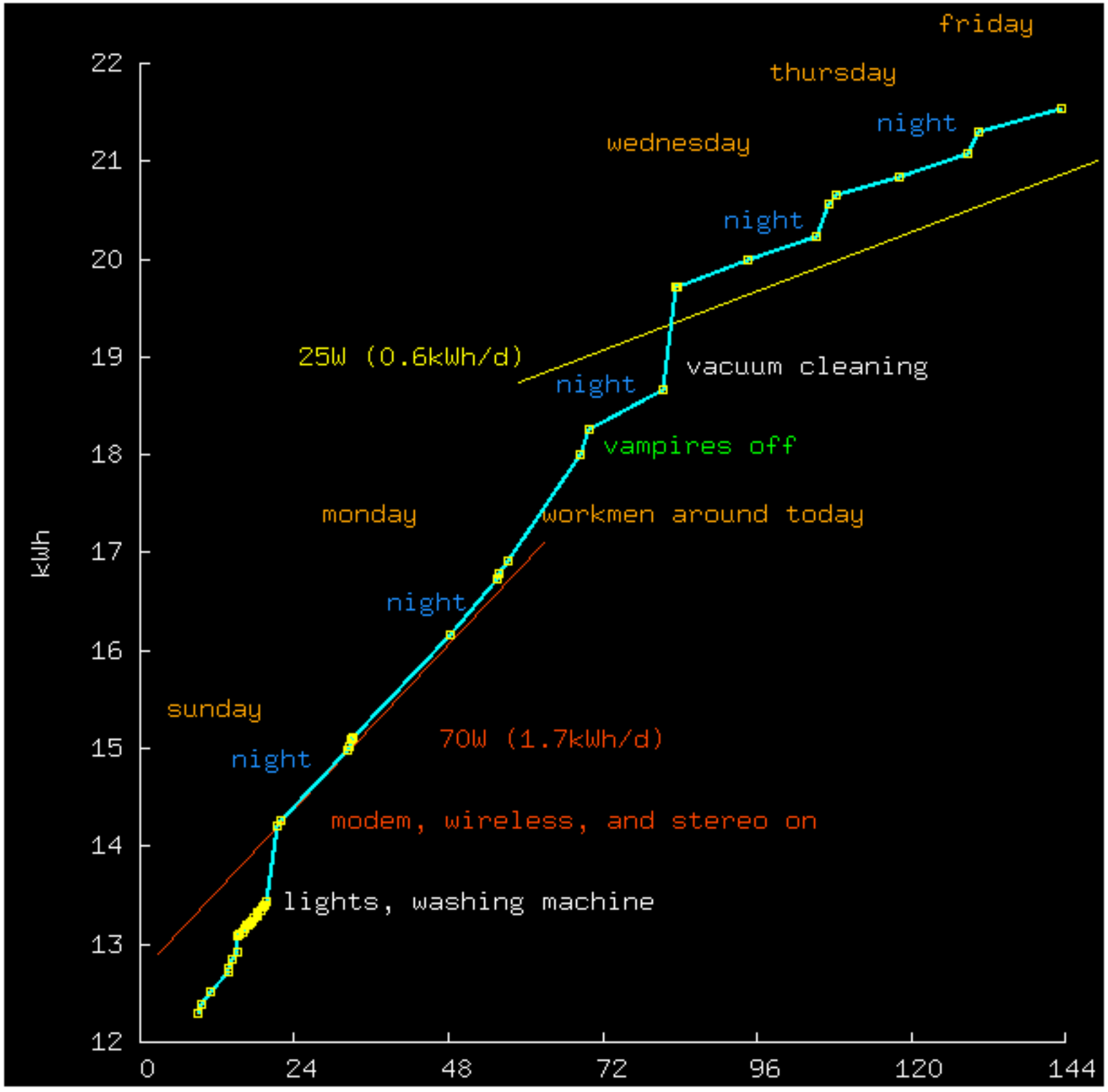
Electricity



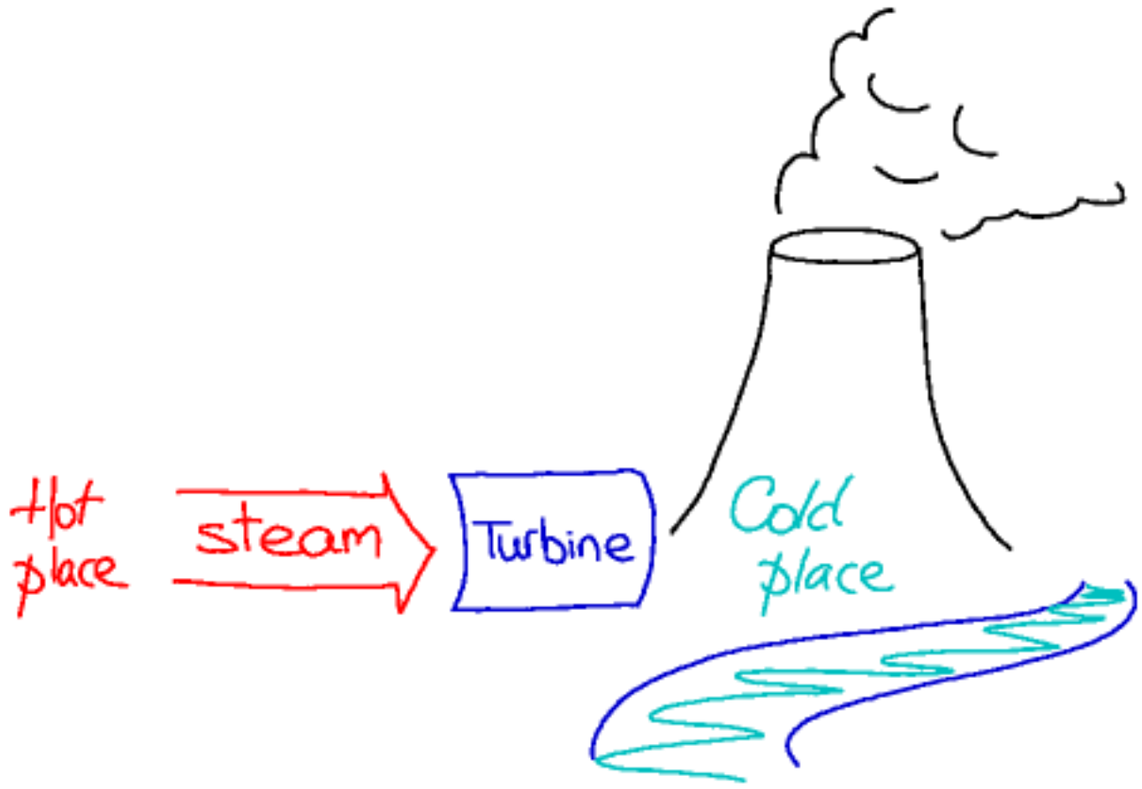


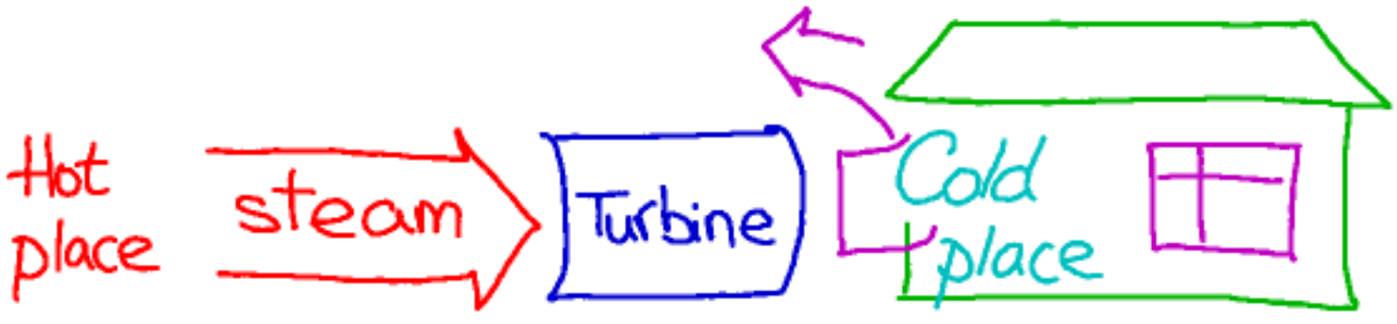
Efficiency III

- Electricity

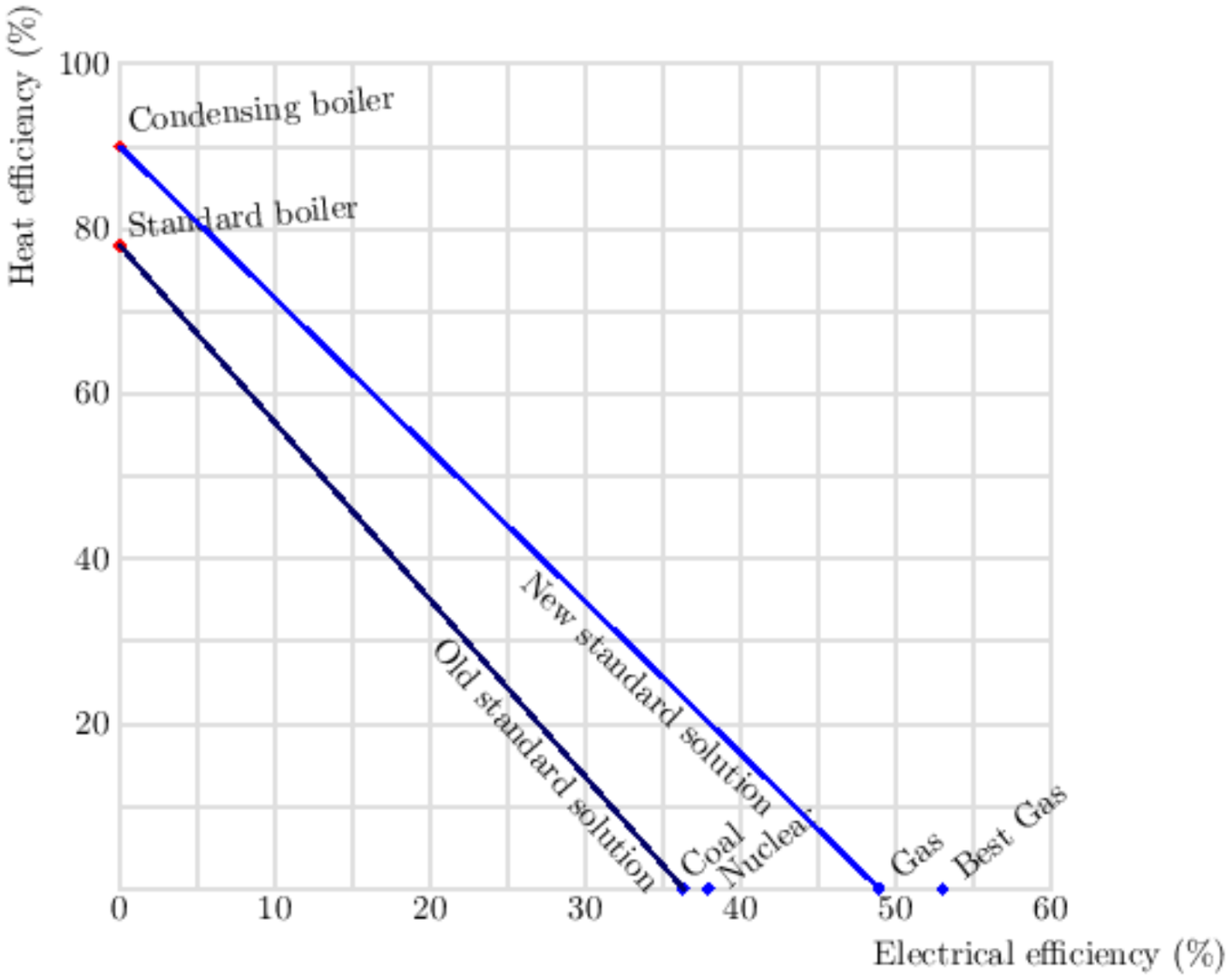


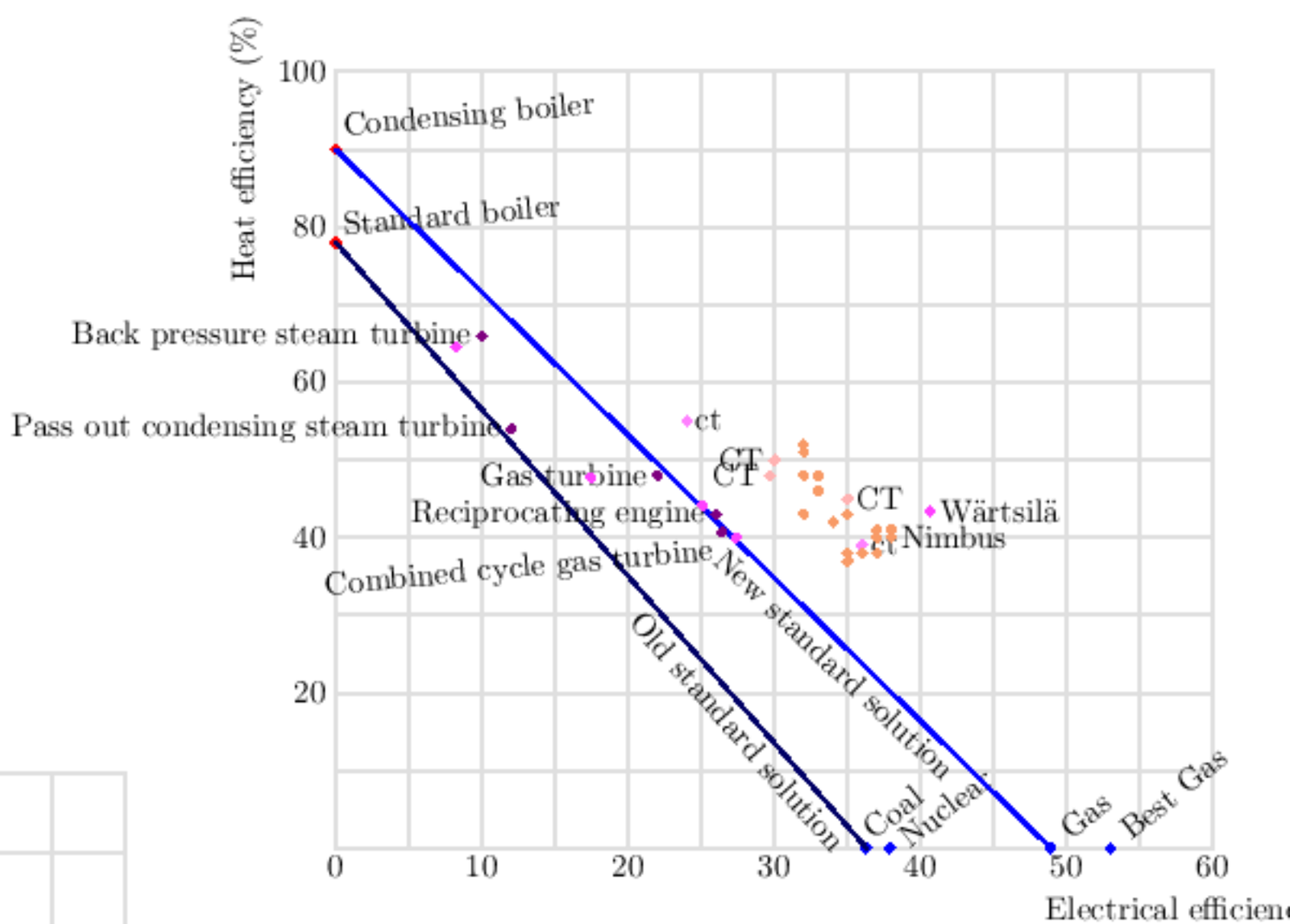
Combined heat and power?





'Microgeneration', 'Decentralization'





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

- Heat pumps

DAIKIN

A world Leader in Air Conditioning Technology

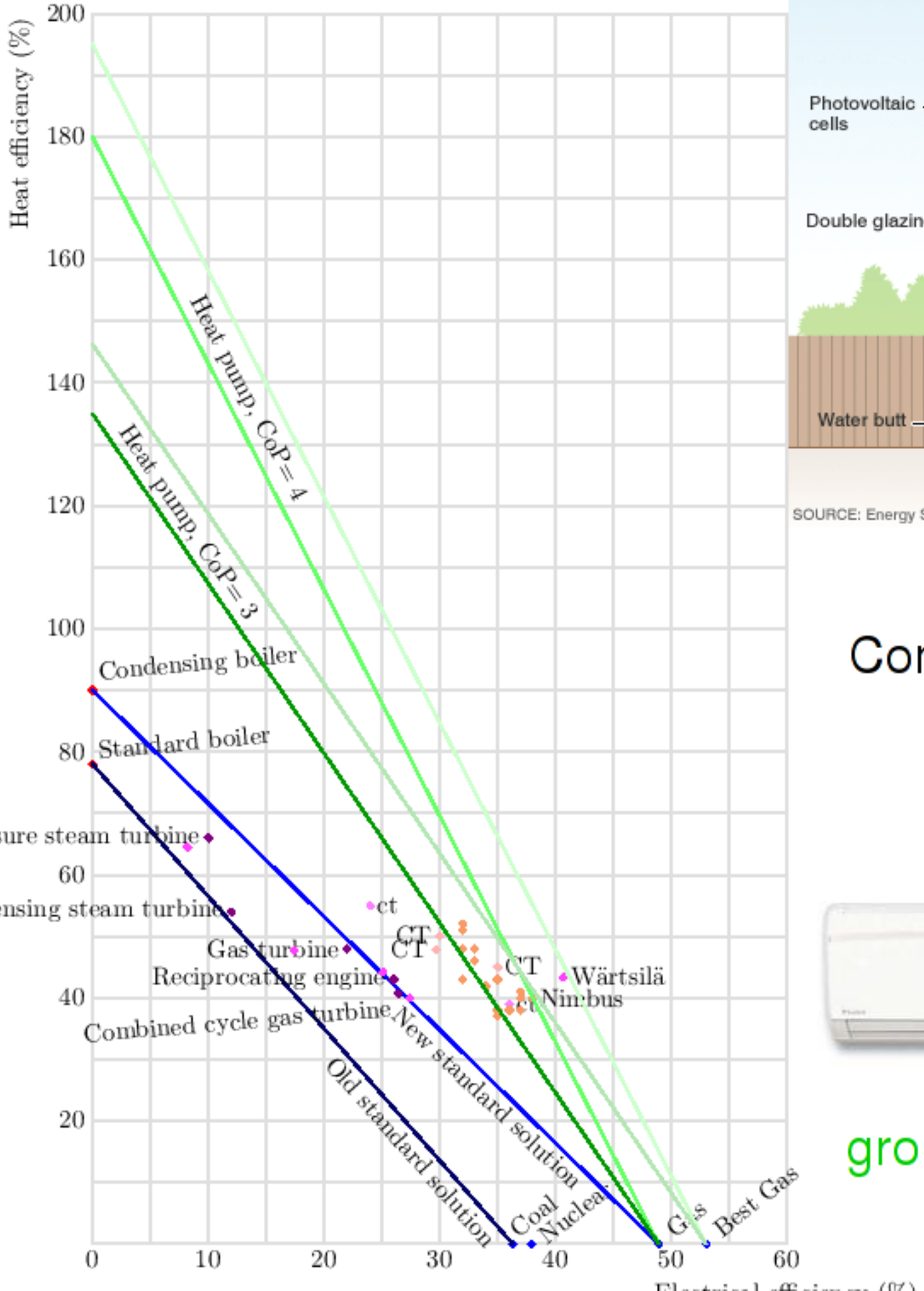
Australia and New Zealand

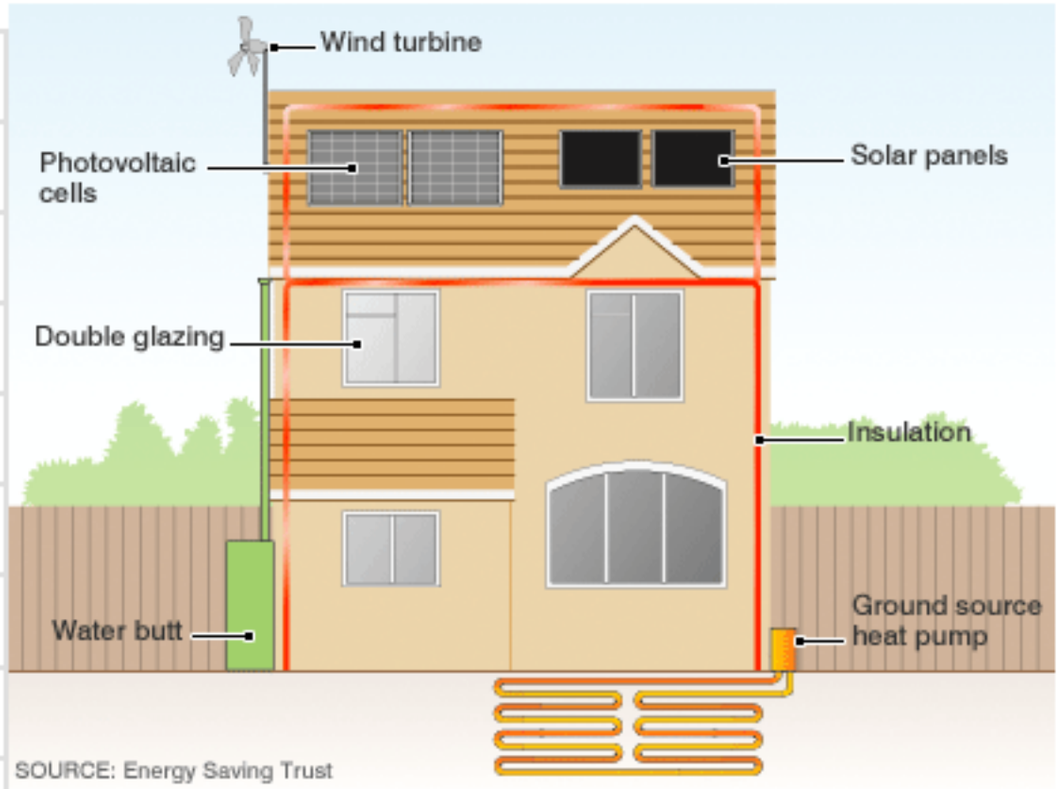
FTXS25E

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.

Unit	Indoor Unit Outdoor Unit	FTXS25EVMA RXS25EAVMA
Rated Capacity	Cool (KW) Heat (KW)	2.5 3.4
Capacity Range	Cool (KW) Heat (KW)	1.2-3.0 1.2-4.5
Indoor Air Flow	Cool (l/s) Heat (l/s)	145 157
Indoor Fan Speeds		5 steps, quiet and automatic
Power Input (min-rated-max)	Cool (kW) Heat (kW)	0.30-0.60-0.80 0.29-0.83-1.34
C.O.P		4.17/4.10
Power Supply		1 phase, 220-240V, 50Hz





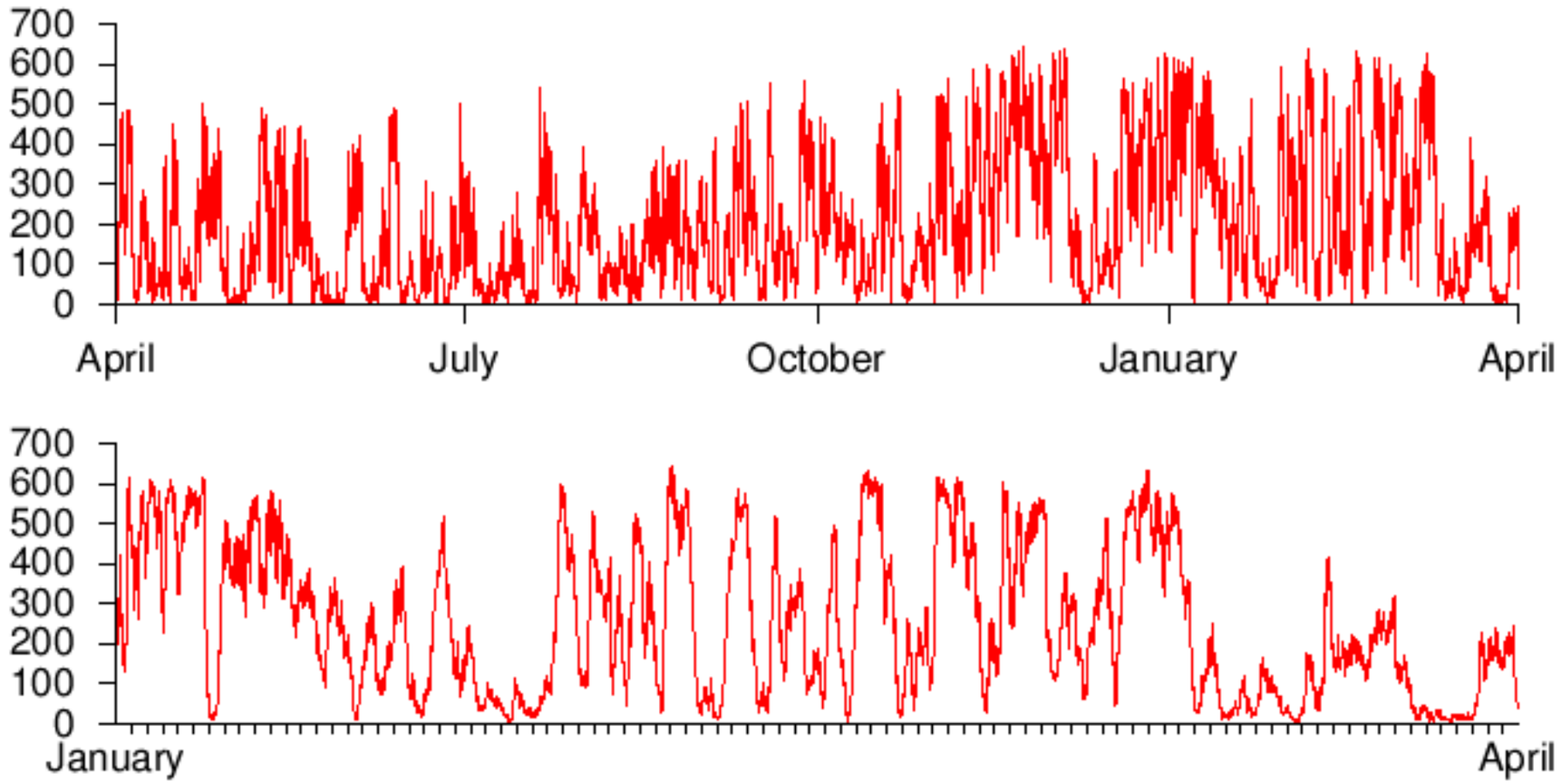
Can we do better than Combined Heat and Power?

- 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'

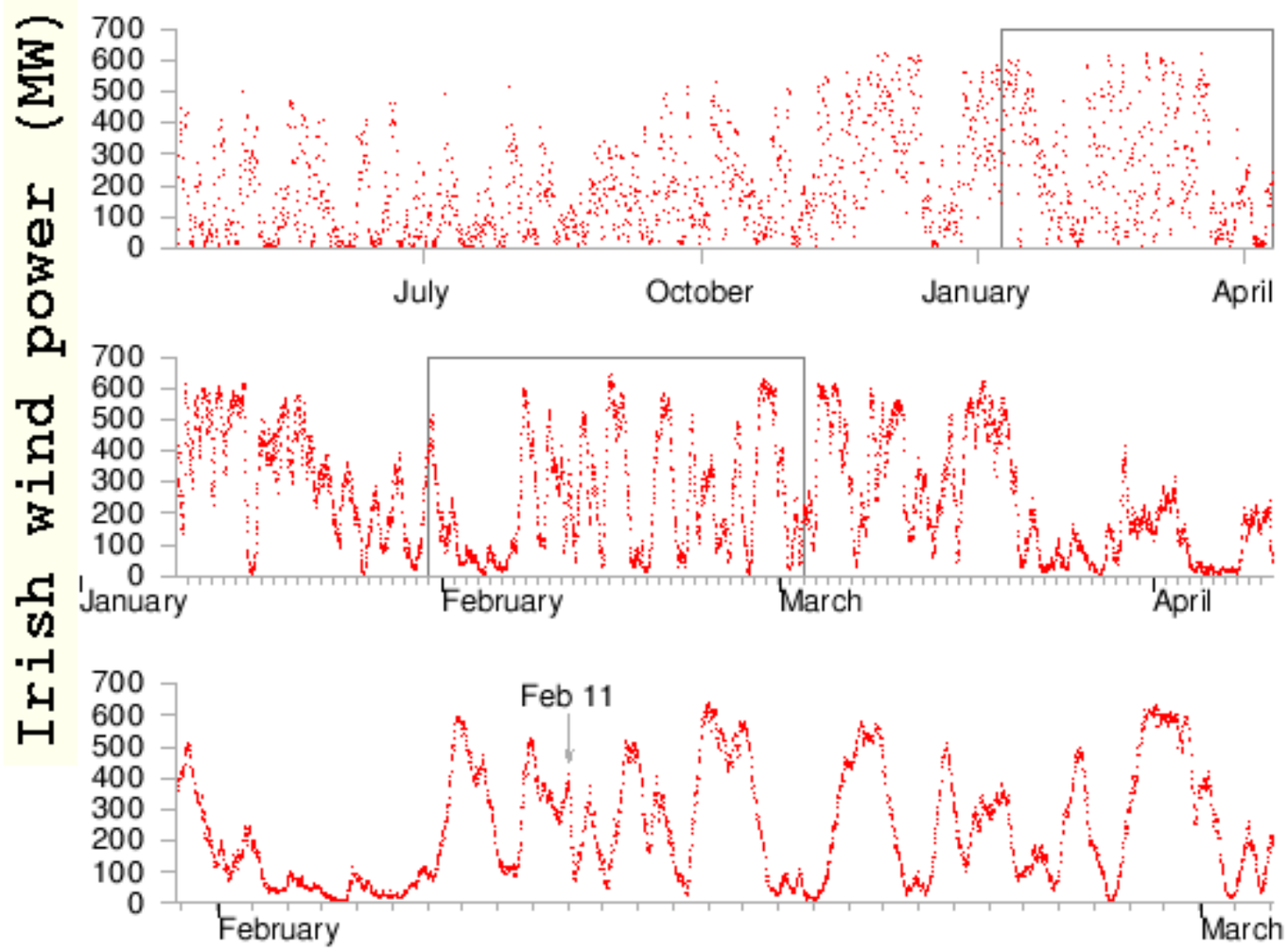
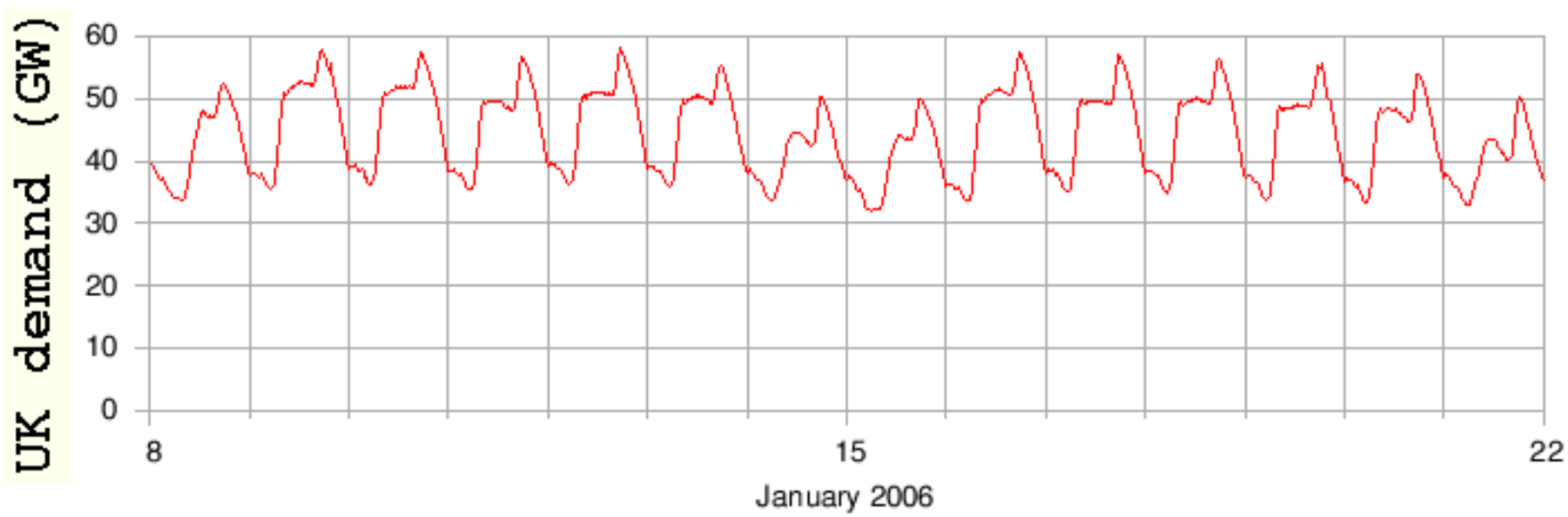


Figure 26.2. Total output, in MW, of all windfarms of the Republic of Ireland, from April 2006 to April 2007 (top), and detail from January 2007 to April 2007 (middle), and February 2007 (bottom). Peak electricity demand in Ireland is about 5000 MW. Its wind 'capacity' in 2007 is 745 MW, dispersed in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

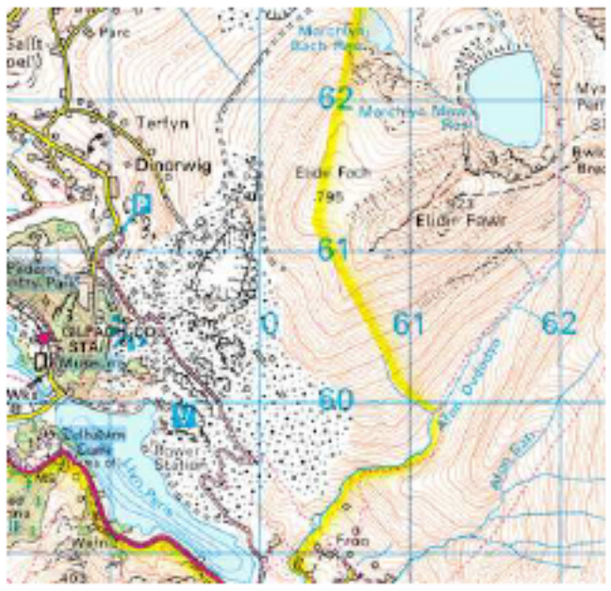
Scale this up: with 33 GW of capacity, expect slew rate of 3.7 GW per hour - an unprecedented problem for Britain?



Every morning, demand rises at a slew rate of 6.5 GW per hour

Storage - more Dinorwigs

Figure 29.2. Dinorwig, in the Snowdonia National Park, compared with Loch Sloy and Loch Lomond. The upper maps show 10 km by 10 km areas. In the lower maps the blue grid is made of 1 km squares. Images produced from Ordnance Survey's Get-a-map service `www.ordnancesurvey.co.uk/getamap`. Images reproduced with permission of Ordnance Survey. © Crown Copyright 2006



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

Okinawa Seawater Pumped Storage Power Plant (0.2 GWh)
www.ieahydro.org
Output - 30 MW

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

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.

The aim is for 20% of EU energy to come from renewables by 2020

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

4%!

4 kWh/d

4 kWh/d

'all homes'

4 kWh/d

10 GW nuclear

4 kWh/d

33 GW wind

Nuclear Fission ('sustainable' = 1000 years)

Uranium

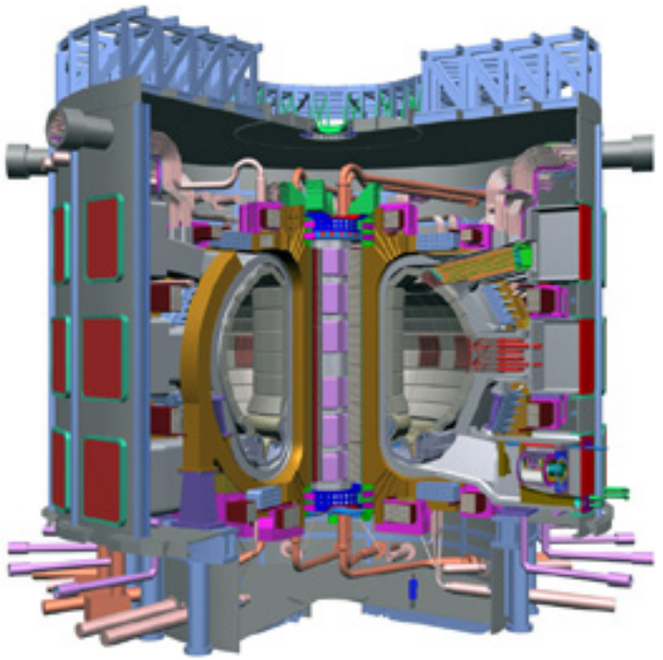
	Mined Uranium	Ocean Uranium	River Uranium
Once-through	.1 kWh/d	7 kWh/d	.08 kWh/d
Fast breeder	5 kWh/d	420 kWh/d	5 kWh/d

Thorium

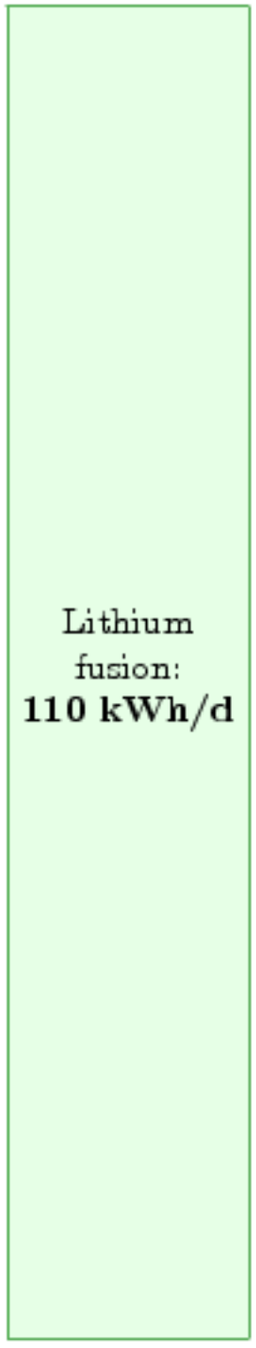
	Mined Thorium
Conventional reactor	4 kWh/d
'Energy amplifier'	60 kWh/d

Nuclear Fusion

- Doable?



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



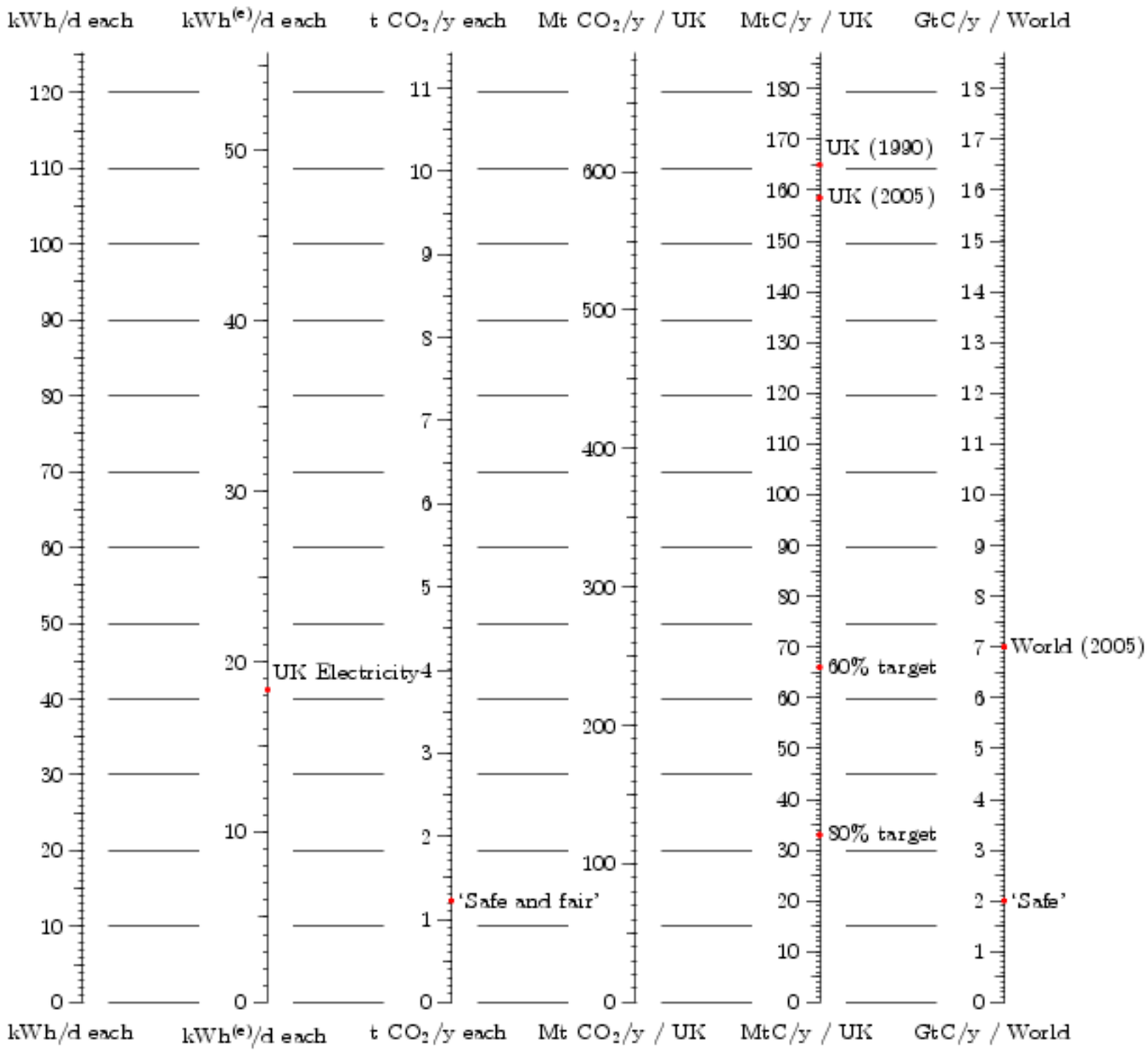
DD reaction

D lasts ~ 1 billion years

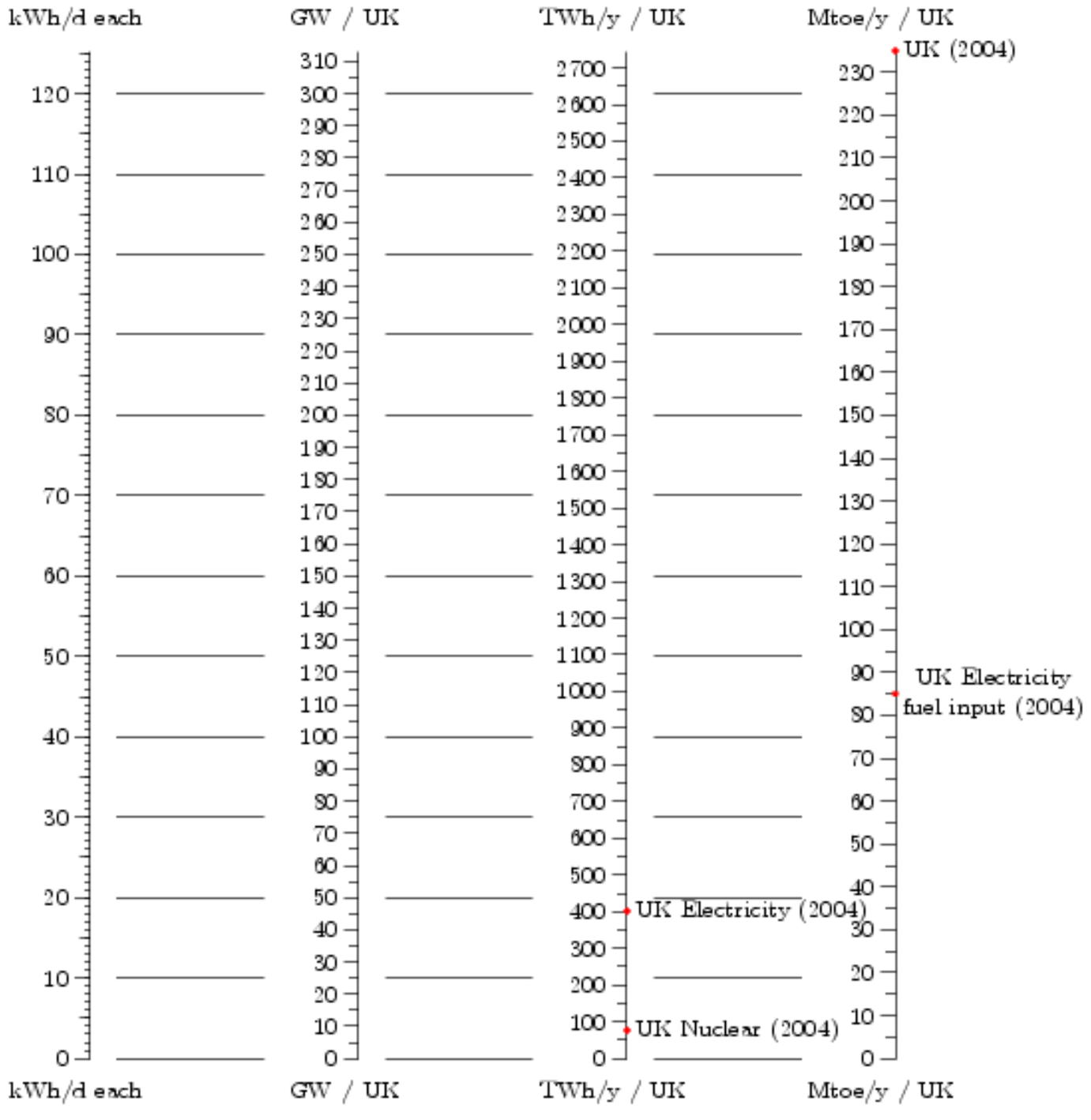
Summary

- 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



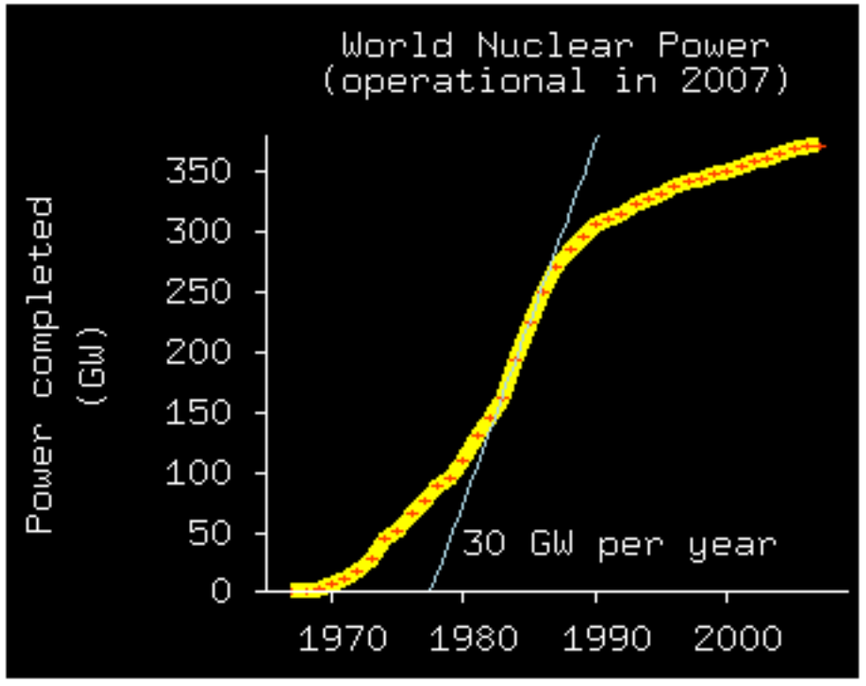
Power translation chart



1 kWh/d	the same as 1/24 kW	'UK'	= 60 million people
GW	often used for '**capacity**' (peak output)		
TWh/y	often used for average output	USA:	300 kWh/d each
1 Mtoe	'one million tonnes of oil equivalent'	Europe:	120 kWh/d each

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)

The truth