A literature survey of UK renewables potential

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1 Introduction

This is a survey of existing studies that estimate the potential for renewable energy in the UK.

It is intended to provide evidence for the numbers in my blog post of 2 September 2015 entitled 'A critique of anti-renewables rhetoric'. Its objective is to answer the question 'how much renewable energy resource is there in the UK?' It considers only studies that cover the whole of the UK and ignores ones that focus only on England, Scotland or Wales.

The studies summarised here have produced estimates that are all over the place. To get round this the highest and lowest estimates for each technology are discarded and the remaining numbers quoted as a range.

The **results** are given in Section 12 on page 51.

Studies on renewable energy resources tend to define various subsets of the total that represent different levels of difficulty, denoted by a more or (usually) less meaningful adjective. The resource-adjectives listed below all appear in the studies surveyed in this paper:

- Total
- Available
- Accessible
- First order
- Second order
- Unconstrained
- Feasible
- Physical
- Natural
- Theoretical
- Technical
- Exploitable
- Extractable
- Achievable
- Realistic
- Realisable
- Practical (usually adorned with an annoying extra syllable, presumably to make it sound more impressive[1])
- Market
- Economic
- Competitive

[1] The Concise Oxford Dictionary gives several definitions of 'practical', the most relevant being 5) 'feasible; concerned with what is actually possible'. It defines 'practicable' as 1) 'that can be done or used', 2) 'possible in practice'. Bill Bryson [1] says: 'Anything that can be done *and* is worth doing is practical. Anything that can be done whether or not it is worth doing is practicable.' It may or may not be unduly paranoid to presume that writers who use 'practicable' do so because they think it is not worth doing.

- Financially viable

None of these adjectives are precisely defined and where different researchers use the same one they seldom attach exactly the same meaning to it. There ought to be an ISO standard that specifies what subsets should be used, what they mean and how they should be calculated. In this paper I have reproduced each study's own definitions, where it has them, in it's own section.

To answer the question 'could we live off renewables if we really wanted to' we need the size of the resource limited only by 'hard' constraints such as built up areas, roads, mountains, lakes and so on. This is often called 'technical' or 'accessible'. This type of constraint is also less reliant on subjective judgement than 'softer' ones such as institutional, socioeconomic and environmental factors.

2 Current deployment

Table 2.1 lists data for the amount of electricity that renewables generated in 2014, taken from DUKES 2014 [2] 'Table 6.4

Table 2.1: Electricity generated from renewables in the UK in 2014 (GWh) (Data from DUKES 2014)

Technology	GWh
Electricity	
Onshore wind	18,611
Offshore wind	13,404
Marine	2
PV	4,050
Hydro	5,885
Landfill gas	5,045
Sewage sludge digestion	846
Biodegradable energy from waste (9)	1,950
Co-firing with fossil fuels	133
Animal Biomass (4)	614
Anaerobic digestion	1,009
Plant Biomass (5)	13,105
Total electricity	64,654
Heat	
Active solar heating	606
Landfill gas	158
Sewage sludge digestion	787
Wood combustion - domestic	18,078
Wood combustion - industrial	5,343
Animal Biomass (9)	401
Anaerobic digestion	500
Plant Biomass (10)	4,339
Biodegradable energy from waste (6)	271
Deep geothermal	9
Total heat	30,493
Transport bio fuels	
Bioethanol	5,336
Biodiesel	9,116
Total transport biofuels	14,451
Total renewables	109,598

Capacity of, and electricity generated from, renewable sources' and augmented from data in Energy Trends June 2015 edition [3]. Figures 2.1 and 2.2 on the facing page show UK renewables output against time starting in 1992.

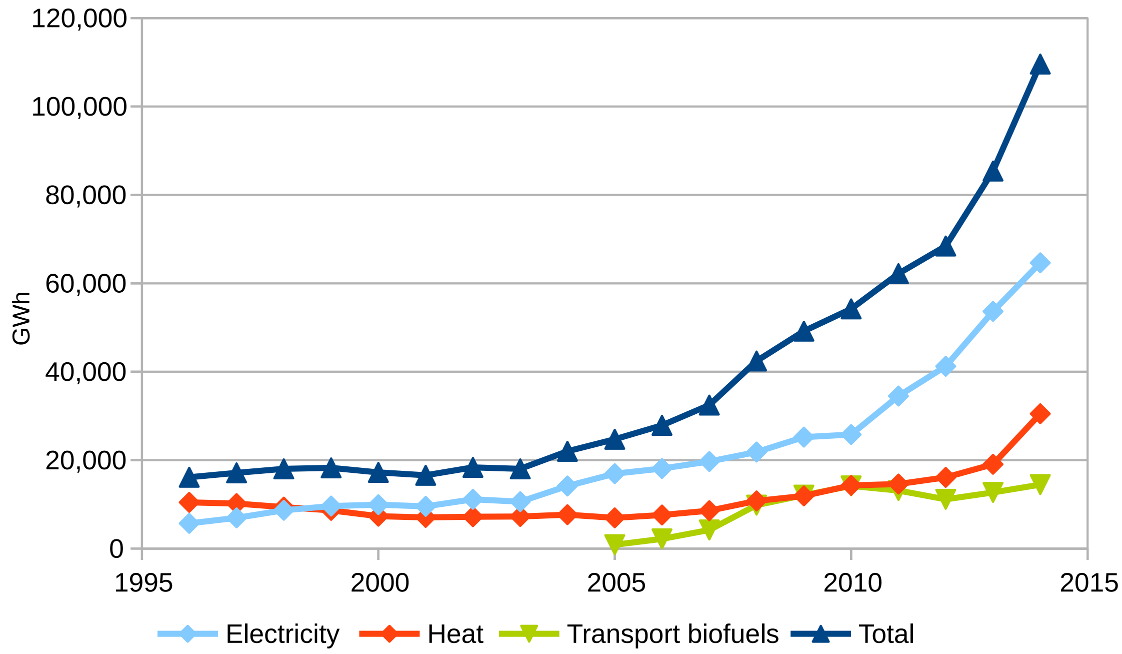


Figure 2.1: UK renewable energy production, 1996 - 2014 (Data from DUKES 2014 and Energy Trends June 2014)

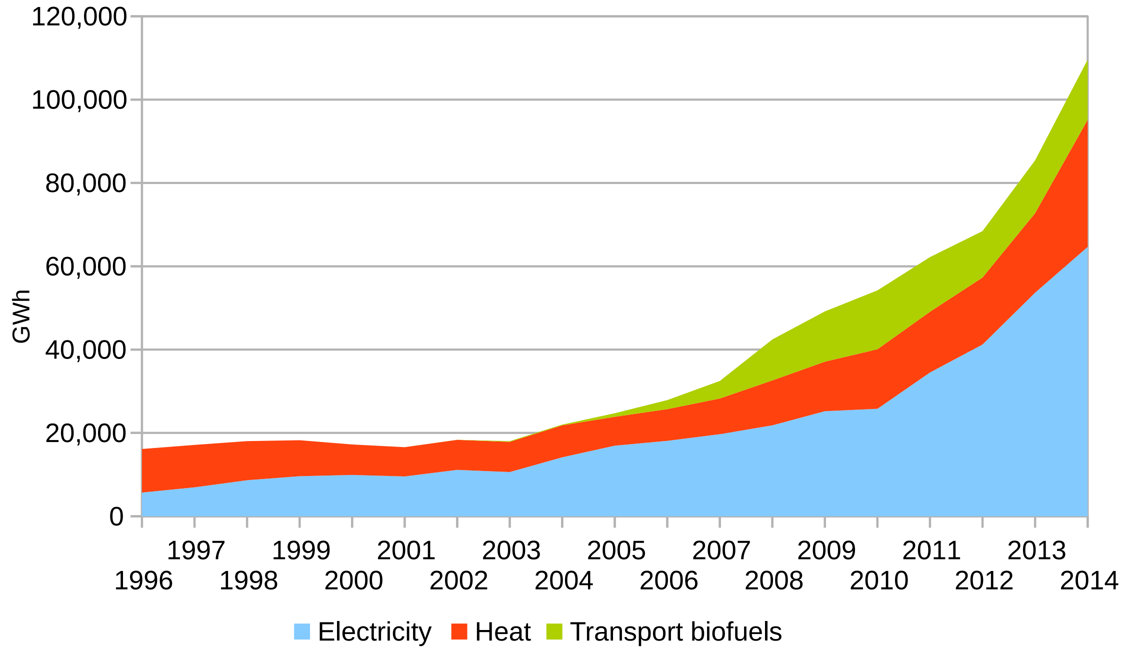


Figure 2.2: UK renewable energy production, 1996 - 2014 (Data from DUKES 2014 and Energy Trends June 2014)

3 Multi-technology studies

A number of books and reports give UK estimates for multiple technologies. This section lists them in order of their date of publication and for each study reproduces relevant information common to all technologies that the study examines. If the study has a summary table it is reproduced in this section otherwise the results appear in the appropriate technology sections below.

3.1 ETSU 1994 [4]

This is a big thick glossy book that was apparently produced as part of a 'strategic review of renewable energy' that the Department of Trade and Industry must have carried out at around that time. It includes some long forgotten technologies such as 'photoconversion', 'passive solar design' and 'hot dry rocks' as well as the more usual ones that are still around today. Its motivation was the identification of research priorities for the government's renewable energy R&D programme. Numbers from this report are reproduced under the relevant technology sections.

3.1.1 Resource adjectives

This study uses two resource categories:

Accessible resource is the resource that would be available for exploitation by a mature technology after only 'primary' constraints are considered. 'Primary' constraints are physical ones such as residential areas, roads, lakes, mountains and so on, and also insurmountable institutional constraints such as national parks.

Maximum practicable resource takes into account more constraints, such as regulatory, sociological and environmental. 'These are often not susceptible to objective scientific assessment and subjective judgements were often required ...'

The report also presents 'resource cost curves' that purport to give the size of the resource that could be developed for less than or equal to given cost of energy. Separate curves are given for the 'accessible resource' and the 'maximum practicable resource'. These are presented in the form of images. The data from which they were plotted are not given.

3.2 DTI 1994, a.k.a. 'Energy paper 62' [5]

This was a shorter report that aimed to set out the government's strategy for renewable energy at that time. It included estimates of the potentials of the main technologies that were derived from those in ETSU 1994.

3.2.1 Resource adjectives

These are identical to those used in ETSU 1994.

3.3 ETSU 1999, a.k.a New and Renewable Energy Prospects for the 21st Century—Supporting Analysis, a.k.a ETSU R-122 [6]

This report updated the earlier ETSU studies to take into account the current situation at the time the report was prepared. It was produced as a supporting document for a consultation exercise, also entitled 'New and Renewable Energy Prospects for the 21st Century' that was put out by the DTI in 1999 [7]. It contains updated versions of the estimates from ETSU 1994 and Energy paper 62.

3.3.1 Resource adjectives

The terms 'accessible' and 'maximum practicable' are used without definition or reference to a definition. Resource cost curves are also presented but the data from which they were plotted are not.

The section on PV uses the terms 'technical potential' and 'market potential' and the section on solar thermal uses 'technical resource' and 'market resource' but these are not used anywhere else in the report.

3.4 Scotland's Renewable Resource, 2001 [8, 9, 10]

This study was undertaken in 2001 by Garrad Hassan and Partners Ltd for the Scottish Executive. Although it only looks at Scotland, in some cases it can be combined with other studies to give estimates for the whole of the UK. Table 3.1 on the next page reproduces its results.

Table 3.1: Results of 'Scotland's Renewable Resource, 2001 [8, 9, 10]

Technology	Capacity (GW)	Energy (TWh/y)
Onshore wind	11.5	45.0
Offshore wind	25.0	82.0
Wave	14.0	45.7
Small hydro	0.3	1.0
Tidal stream	7.5	33.5
Landfill Gas	0.07	0.555
Forestry Residues	0.09	0.7
Energy Crops	0.14	1.1
Agricultural Wastes	0.4	3.5
Municipal Solid Waste (MSW)	0.1	0.9
TOTAL	59.1	213.955

3.5 Chapman and Gross, 2001 [11]

This report was produced as part of a review of energy policy carried out in 2001 by the 'Performance and Innovation Unit' (PIU), later rebranded the 'Prime Minister's Strategy Unit' ('. . . an elite unit based in the UK Cabinet Office between 2002 and 2010 (with its predecessor unit dating back to 1999)' [12]).

The overall PIU project [13] was called 'The Energy Review'—implying that it is the only energy review that has ever been done by anyone at any time. It was carried out by a team of 18 researchers plus eight part-time consultants. The team consulted with, or received submissions from, 563 organisations or individuals. Although the review produced a 216-page final report, also entitled 'The Energy Review', its data and analysis are contained in a series of twelve sub-contracted study reports, called 'working papers', of which Chapman and Gross's is one.

They state that their numbers are taken from ETSU 1999. They have collected them together into one table, whereas in ETSU 1999 they were spread randomly through the report, and have also cast them into four categories ('available', 'technical', 'practicable' and 'economic') from the original two ('accessible' and 'maximum practicable'). This must have taken a lot of effort.

3.5.1 Resource adjectives

Chapman and Gross define their resource subsets as follows:

Available resource refers to the total amount of different forms of renewable energy available for extraction – for example the energy in ocean waves, or solar insolation levels. For several technologies (essentially solar, wind, tidal, wave and biomass), UK available resource is very large indeed.

Technical potential (also referred to as accessible resource) refers to the amount of energy that might be extracted from the available resource, using known technologies (note that for future technologies judgements are required, for example about conversion efficiencies – will they improve, how much?). Again, for a number of technologies, technical potentials are very large – taken together they exceed UK primary energy consumption several times over.

Practicable potential (also referred to as practicable resource) refers to the amount of the technical potential that might reasonably be accessed, taking into account various technical and physical limiting factors such as competing land (and ocean) use and often includes further limitations, such as electricity grid and system constraints. A closely related concept (definitions of terms do differ) is accessible potential. Practicable resource is more difficult to assess in the long term, since many constraints may change over time as technologies progress, or reflecting different political/societal priorities (affecting land-use priorities for example). For the latter reason, it also tends to show significant variation between studies in different parts of the world. Economic potential refers to the amount of accessible potential that is economically viable, given current technology, or with future, better (and cheaper) technologies.

Economic potential depends upon the cost of alternative/competing energy sources, which for the UK generally means conventional means of generating grid electricity (though some renewables can also provide heat, and there are some niche markets such as remote telecommunication/navigation where the electrical alternative is not grid power). It is important to note that policy may influence both the development of renewables and the cost of conventional competitors – for example though a carbon tax.

3.5.2 Results

Table 3.2 reproduces Chapman and Gross's Table 1 on Page 5[2] their report, together with the original footnotes.

Table 3.2: 'DTI estimates of Resource and cost in 2025 (derived from DTI 1998)' (Table 1 of Chapman and Gross 2001 [11], with original footnotes.)

Technology	Cost* p/kWh	Economic potential at this cost* TWh/yr	Technical potential TWh/yr	Practicable potential TWh/yr
Building integrated photovoltaics (BIPV)	7	0.5**	266	37**
Offshore wind	$2.5 - 3.0$	100	≈ 3500	100
Onshore wind	< 3.5	58***	317	8****
Biomass (energy crops)††	4	33	'large'	'large'
Wave	4	33	600	50
Tidal stream†	7	1.8	36	1.8
Small Hydro	7	1.8	40	3
Waste technologies: MSW	7	6.5	13.5	6.5
(municipal solid waste) Landfill gas	2.5	7	7	7

This table is an interpretation and simplification of the DTI analysis, therefore some caution is needed in interpreting these figures: 'Technical potential' here is termed 'accessible resource' in the DTI study and practicable potential is termed practicable resource. This is in order to convey that all figures are for potentials – potential energy output, not available resource input.

* ETSU for the DTI, derive 'resource cost' curves for all technologies, that increase with cost, in most cases up to a maximum level at which external (practicable potential) constraints cut in. The costs quoted are those at which this maximum level of deployment would be achieved. The exception is BIPV, where only the potential at less than 7p/kWh is included, significantly larger potential would be available at higher cost.

** BIPV practicable potential is limited by assumptions about penetration rate into new buildings, economic potential to even lower penetration of those new buildings with potential for offset building costs.

*** Assumes minimal constraints due to planning, network and build rate. But...

**** Assumes constrained build rate and no network reinforcement – hence the somewhat counterintuitive result that economic potential is higher than practicable potential.

† Tidal stream devices exclude large barrages, ruled out by the DTI on capital cost and environmental grounds. Practicable potential/resource is not provided in the study for this technology type

†† Assessment restricted to energy crops for the purposes of this analysis for reasons discussed below, additional contributions are assessed in the DTI work – from forest and agricultural wastes and residues, and from other biodegradable wastes. The DTI assessment also includes passive solar design and solar hot water, although important these are dealt with in the paper on energy productivity because of the close overlap with building efficiency. For similar reasons we also deal with ground source heat pumps in the energy efficiency paper.

3.6 Boyle et al, 2nd edition [14]

This is a textbook dedicated to an Open University course. I have the 2nd edition, though the 3rd has been out for a while now. Table 3.3 on the next page shows their numbers. The authors state that these numbers come from Chapman and Gross, 2001 [11]. Table 3.2 reproduces Chapman and Gross's numbers for comparison.

3.6.1 Resource adjectives

The subsets of the resource to which the numbers refer are defined as follows:

Available resource (or 'total' resource) – the total annual energy delivered by the source; for example the total energy carried by ocean waves or the wind, or the total incident solar energy.

[2] Chapman and Gross 2001 [11] has no page numbers. Table 1 is on the fifth page of the document numbered from the front cover.

Table 3.3: UK renewables potential (reproduced from Table 10.1 on page 390 of Boyle et al 2004 [14])

Technology	Technical potential ($TWh\,y^{-1}$)	Practicable potential ($TWh\,y^{-1}$)	Cost (p/kWh)	Economic potential at this cost ($TWh\,y^{-1}$)
Building integrated PV	266	37	7.0	0.5
Offshore wind	≈ 3500	100	2.5 – 30	100
Onshore wind	317	8* – 58	<3.5	58
Biomass (energy crops)	'large'	'large'	4.0	33
Wave	600+	50	4.0	33
Tidal stream	36	1.8	7.0	1.8
Small hydro	40	3	7.0	1.8
Municipal solid waste	13.5	6.5	7.0	6.5
landfill gas	7	7	2.5	7
Total	4779.5	263.3		241.6

Technical potential (also referred to as *accessible resource* – the maximum energy that coukld be extracted from the accessible part of the Available Resource using current mature technology. Although this could change with technological advances, it may ultimately be limted by teh laws of physics (determining for instance the properties of wind turbines or the efficiency of heat engines.) It is also limited by basic accessibility constraimnts due to:

- practical difficulties such as the opresence of roads, buildings and lakes,
- institutional restrictions and the needn to avoid areas such as National Parks, Sites of Special Scientific Interest (SSSIs), Areas of Outstanding Natural Beauty (AONBs), etc.

Practicable potential (also referred to as the *practicable resource* – the technical potential reduced by taking into account:

- constraints on using or distributing the energy – such as transportation problems, access to the electricity grid or problems of intermittent supply,
- further limitations on land or technology use due to public acceptibility. It may be difficult to quantify these, since they may only become apparent when planning permission is sought and environmental objections are expressed.

Economic potential – the amount of the technical potential that is economically viable. Any judgement about this requires the specification of an acceptable energy price and a discount rate that sets the cost of brorrowing money for investment.

3.7 MacKay 2009

In his book *Sustainable Energy without the Hot Air* [15], Professor MacKay derives all his numbers from scratch in an appealing back-of-the-envelope kind of way, showing all his workings. This is a pleasant contrast to the opaque computer 'modelling' that is the norm in the 'policy community'. Don't you just hate the phrase 'our modelling shows that ...'?

Prof MacKay uses units of kWh/day/person. This is based on a UK population of 59.5 million broken down as follows:

Table 3.4: Population estimates used in MacKay 2009 [15], with ONS data for comparison

	Land area km^2	Population (million) MacKay 2009	ONS for 2005 [16][a]	ONS for 2013
England	130,000	49.6	50.6	53.9
Wales	20,700	2.91	3.0	3.1
Scotland	78,700	5.05	5.1	5.3
Northern Ireland	not stated	1.04	1.7	1.8
UK	244,000	59.5	60.4	64.1

[a] The ONS estimates are described as 'revised'. I presume the revision must have happened after Professor MacKay's book was published. The difference is small.

3.7.1 Resource adjectives

Professor MacKay does not use resource adjectives (hooray!).

4 Onshore Wind

4.1 Grubb and Meyer 1993 [17]

This is the earliest published estimate of the UK's wind energy potential that I have been able to find. Many subsequent studies refer to it and/or recycle its results.

4.1.1 Resource adjectives

First-order potential excludes 'indisputable constraints' such as:

- cities;
- forests;
- unreachable mountain areas.

Second-order potential excludes social, environmental and land-use constraints, including (and perhaps dominated by) visual impact, all of which depend on political and social judgements and traditions, and vary from country to country.

4.1.2 Results

Table 4.1 reproduces its Table 8 (page 193).

Table 4.1: Wind electric potentials in Europe (Table 8 of Grubb and Meyer 1993 [17])

Country or region	Gross electrical potential [a] TWh/y	Population density $People\,per\,km^2$	First-order potential TWh/y	Second-order potential TWh/y	1989 Electricity production TWh/y
Denmark	780	120	38 onshore	10 onshore 10 offshore	26
United Kingdom	2,600	235	760 onshore	20–150 onshore 200 offshore	285
Netherlands	420	360	16 onshore	2 onshore	67
EC [a, b]	8,400	140	490 onshore	130 onshore	1,600
Norway		13.1		12 [d]	109
Sweden	540 [e]	19	32 [c]	30 [f]	140
Finland		14.7	30 [g]	10 [g]	41

[a] See the section on "Technical Assumptions" (p. 28) [Note, the section referred to appears on page 186 of the book, which is the 30th page of the chapter].
[b] Exclusion factors as for Denmark; see text.
[c] For the whole Norwegian coast, including small island-cliffs [46].
[d] Using only the best sites along the coast [46].
[e] Includes southern Sweden only, and only areas with mean annual wind power densities higher than 450 W/m^2 at 100m height. Offshore sites at 6 to 30 meters depth and more than 3 kilometres from land are also included [47].
[f] About $7TWh$ per year at land and $23TWh$ per year offshore [48].
[g] Including some offshore sites [48].

4.2 ETSU 1994 [4]

4.2.1 Accessible

This says (page 46):

> **Accessible Onshore Resource**
>
> The total over all land classes provided an estimate of the available resource as a function of AWMS; the total over all wind speed bands gave a total accessible resource in the UK of about $\boxed{340TWh/year}$, reflecting the windy nature of the British climate.
>
> The accessible resource for specific areas in the UK are: England & Wales $120TWh/year$, Scotland $190TWh/year$ and Northern Ireland $33TWh/year$. For comparison, the annual electricity consumption in the UK is around $300TWh/year$.

4.2.2 Maximum practicable

Table 4.2 reproduces the estimates of maximum practicable resource:

Table 4.2: Maximum practicable resource available at $\leqslant 10p/kWh$ (Table 9 p51 of ETSU 1994 [4])

	Discount rate (%)	England and Wales	Scotland	Northern Ireland	UK
Maximum practicable resource 2005 and 2025 (TWh/y)	8	11	36	5	52
	15	10	35	4	49

4.3 DTI 1994

Page B3:

> The UK has the best wind resource in Europe. There are limitations on the availability of land for wind turbine sites due both to physical constraints—such as the presence of towns, villages, lakes, rivers, woods, roads and railways—and institutional constraints such as the protection of land areas designated as being of national importance. Also, wind turbines have to be located some distance from habitation for environmental reasons. Offshore there is potentially a very large wind resource but it will require additional technology development before it can be effectively exploited.

Table 4.3 reproduces its results, which were stated to be from ETSU 1994.

Table 4.3: UK Wind Energy resource (from DTI 2004 [5])

	Accessible Resource (TWh/year) at less than 10p/kWh (1992). 8% discount rate.	Maximum Practicable Resource (TWh/year) in 2005 at less than 10p/kWh (1992). 8% discount rate.
Onshore Wind	340	55*
Offshore Wind	380	0

* assuming no limitation imposed by integrating into the grid.

4.4 Brocklehurst 1997 [18]

This study reports the first use of a geographical information system to model the UK's onshore wind resource. I cannot find it anywhere on the internet so I have put a copy on my website here.

4.4.1 Resource adjectives

Feasible is defined as '. . . an estimate of the resource if areas which are unsuitable for siting wind turbines for physical reasons are removed from consideration'.

Accessible is defined as '. . . a refinement of the feasible resource whereby areas which are more sensitive to the environmental impact of wind energy development are further excluded from consideration'.

Practicable is defined as '. . . the accessible resource . . . limited by three further restrictions:

- the need to group wind turbines together so that they are financially and practically viable and to minimise their environmental impact
- the rate at which the wind farms can be built
- the restriction placed on the resource by the limits of the electrical network

When these restrictions are applied to the accessible resource the remainder is called the "practicable resource".

4.4.2 Results

Table 4.4 reproduces the results.

Table 4.4: UK onshore wind estimates from Brocklehurst 1997

	Feasible (GWh/y)		Accessible (GWh/y)		Maximum practicable (GWh/y)	
	All	$\geqslant 7m/s^*$	All	$\geqslant 7m/s^*$	2005	2025 (optimistic)†
England	372,865	121,182	222,712	36,975		
Wales	59,181	32,869	34,844	16,055	1,380	12,850
Scotland	507,843	428,357	246,761	208,601	936	16,500
Northern Ireland	105,736	78,380	79,099	56,223	142	650
Total	1,045,626	660,787	583,416	317,854	2,458	30,000

* Subset of the resource excluding places where the annual mean wind speed, at a height of $45m$ above ground level, is less than $7m/s$.

† The 'pessimistic' case is stated to be the same as 2005, but is not given explicitly.

4.5 ETSU 1999 [6, page 178]

This says (page 178):

Estimation of Resource

The method of estimating the UK resource has been refined over recent years by the application of improved computational modelling combined with the use of a geographical information system (GIS). This has made it easier to incorporate new data and produce more reliable estimates. One part of that data is accurate 'Ordnance Survey' map information, and another is an assessment of land-use using satellite remote-sensing.

The first stage of resource estimation is to calculate the resource excluding areas where wind turbines could not be placed for physical reasons (the presence of towns, villages, lakes, roads, rivers, woods, etc). This is called the feasible resource. To do this, 21 different types of land cover, distinguishable from the satellite data, have been rated either suitable (e.g. 'arable land') or unsuitable (e.g. 'beach') for siting turbines. The other parameters and assumptions used in the estimation are as follows:

- Wind power conversion by 600kW turbines of hub height 45m above ground level.
- A maximum turbine density corresponding to 9MW/km^2 (equivalent to 15 turbines per km^2).
- Reduction of the resulting resource by: - 2% to allow for availability of the turbine - 5% to allow for wake losses - 5% to allow for electrical losses.

- An actual turbine density based on the land cover class for each km^2 considered, i.e. no turbines would be counted as placed on the 'unsuitable' fraction of a kilometre square.
- Further exclusion of areas comprising buffer zones, ie:
  - 100m buffer either side of roads, rivers, etc
  - 100m buffer around wooded areas
  - 400m buffer around settlements - exclude areas sloping at more than 10° to the horizontal
  - 6,000m buffer zone around airports.

Accessible Resource

The accessible resource refines the feasible resource by taking into account nationally designated areas which would be considered unsuitable for wind turbines because of their impact on the environment. These areas include National Parks, AONBs, National Nature Reserves, SSSIs, and green-belt land. The resource is then calculated using wind speed data for 45m above ground level, with the exclusion of areas having wind speeds less than 7m/s (this implies equivalently a cost of electricity greater than or equal to around 4.5p/kWh at 8% rate of return over 20 years).

With these refinements, the accessible resource (available to the notional turbines) is as shown in Table 6.

	Installed capacity (MW)	Annual Energy Output (GWh/year)
England and Wales	20,291	53,030
Scotland	68,824	208,601
Northern Ireland	20,564	56,223
UK Total	109,679	317,854

It should be noted that this comprises a very significant increase compared with the equivalent previous (1994) estimates.

The report then goes on to discuss further constraints on deployment, including *build rate*, *network constraints* and *planning*, but the discussion is difficult to follow. It says:

> The result is to reduce the UK resource dramatically, from $19,469MW$ to just $2,750MW$, or equivalently $8,180GWh/year$, which is roughly 2.7% of the UK's current energy requirements. The major reductions occur for Scotland and Northern Ireland, to just 300MW and 50MW respectively.

The quantities $19,469MW$; $2,750MW$ and $8,180GWh/year$ appear nowhere else in the report, so it is impossible to understand where they came from.

Interestingly, in 2013 onshore wind generated $16,992GWh$ (see Table 2.1 on page 2). This is more than twice the figure of $8,180GWh/year$ quoted above.

4.6 DTI Wind Energy Fact Sheet 8—The UK wind resource [19]

This was published in January 2001. It says:

> It is theoretically possible to obtain more than $1000TWh$ of electricity each year from the wind in the UK. This is almost three times the amount of electricity actually used. To obtain an understanding of the practicable resource, account must be taken of sensible restrictions, such as protected areas and the utilisation of only the more economic sites. ETSU's estimate of the likely practicable resource is something over $50TWh$ per year on land – for information on the offshore resource see Fact Sheet 1.

The document says that the figures are from Brocklehurst, 1997 [18].

4.7 Leithead 2007 [20]

This paper was published in a special issue of of *Phil Trans Roy Soc A* called "Discussion Meeting Issue 'Energy for the future' organised by Katherine Blundell and Fraser Armstrong". It says:

> In comparison to the UK annual electricity demand of roughly 350TWh yr^{-1}, it would be technically feasible, but not practical, to generate 1000TWh yr^{-1} of electricity from wind. Instead, the accessible and economic

resource is approximately 150TWh yr^{-1}. Onshore wind power could contribute in the region of 50TWh yr^{-1} and offshore wind power could contribute in the medium term 100TWh yr^{-1}.

The paper provides no reference or derivation of these figures, though it seems to imply that they are from the European Wind Atlas. This is a commercial product offered by WaSP of Denmark [21] but was originally developed in 1985 by Riso National Laboratory with EU FP1 funding [22]. The atlas is not available free of charge, so I have not been able to look at it.

4.8 MacKay 2008

The chapter on wind starts on page 32 (pdf 45), but actual derivations of quantities are presented in Appendix B: 'Wind II', on page 263 (pdf 276).

Assumptions:

- Average wind speed = $6m/s$
- Air density = $1.3kg/m^3$
- Coefficient of performance = 50%
- Inter-turbine spacing $\ell = 5$ rotor diameters
- Land area of UK = $244,000\,km^2$

Power is given by

$$p = C_p \pi \left(\frac{d}{2}\right)^2 \frac{1}{2} \rho v^3$$

assume the turbines are in a square array of side $\ell = 5d$, then:

$$power\,per\,unit\,land\,area = \frac{C_p \pi (d/2)^2 \frac{1}{2} \rho v^3}{(5d)^2}$$

the diameter cancels out, so

$$\begin{aligned} power\,per\,unit\,land\,area &= \frac{C_p \pi (1/2)^2 \frac{1}{2} \rho v^3}{5^2} \\ &= \frac{C_p \pi \rho v^3}{8 \times 25} \\ &= \frac{0.5 \times \pi \times 1.3 \times 6^3}{8 \times 25} \\ &= 2.2054\,W/m^3 \end{aligned}$$

round to 2 sig-figs

$$power\,per\,unit\,land\,area = 2.2\,W/m^3$$

apply to UK land area of $244,000\,(km)^2 = 244 \times 10^9 m^2$:

$$\begin{aligned} 2.2\,W/m^3 \times 244 \times 10^9 m^2 &= 2.2 \times 244 \times 10^9 W \\ &= 8,760 \frac{h}{y} \times 2.2 \times 244 \times 10^9 W \\ &= 8,760 \times 2.2 \times 244 \times 10^9 Wh/y \\ &= 4,702,368 \times 10^9 Wh/y \\ &= 4,702.368 \times 10^3 \times 10^9 Wh/y \\ &= 4,702.368 TWh/y \end{aligned}$$

rounding to 2 sig-figs:

$$\boxed{4700 TWh/y}$$

.

He then says:

> Let's be realistic. What fraction of the country can we really imagine covering with windmills? Maybe 10%?
>
> I should emphasise how generous an assumption I'm making. Let's compare this estimate of British wind potential with current installed wind power worldwide. The windmills that would be required to provide the UK with 20 kWh/d per person amount to 50 times the entire wind hardware of Denmark; 7 times all the wind farms of Germany; and double the entire fleet of all wind turbines in the world.
>
> Please don't misunderstand me. Am I saying that we shouldn't bother building wind farms? Not at all. I'm simply trying to convey a helpful fact, namely that if we want wind power to truly make a difference, the wind farms must cover a very large area.

10% of the above figure is $\boxed{470TWh/y}$. This is roughly ten times the figure of $50TWh/y$ quoted in several of the above estimates, though roughly in the same ball park as the $317.8TWh/y$ quoted in ETSU 1999. Dividing by the UK population quoted in the book (59.5×10^6) and dividing the answer by 365 gives $21.6kWh/d/person$ which, when rounded to 1 sig-fig agrees with professor MacKay's figure of $20kWh/d/person$.

4.9 EEA 2009. [23]

This report is strange. It presents a very accurate estimate of Europe's onshore wind energy potential, derived using a GIS database containing wind speeds and ground heights at high spatial resolution. However, despite being subtitled 'An assessment of environmental and economic constraints', the results are calculated as if Europe were entirely unpopulated. The environmental and economic constraints are taken into account as follows.

Environmental constraints

This is done by excluding 'Natura 2000' sites. Every m^2 that is not a Natura 2000 site in included.

Economic constraints

These are taken into account by calculating the cost of energy as a function only of wind speed. The capital and operating costs of a wind farm are assumed to be the same everywhere, but the revenue depends on wind speed. The result is that some less windy parts of Europe are deemed 'not competitive' and are excluded from the total. All of the UK is categorised as 'competitive'.

Results

The end result is that the EU-27's onshore 'competitive' wind energy potential is $25,102TWh/y$, while the UK's is $4,404TWh/y$. This is roughly similar to Professor MacKay's figure of $4700TWh/y$ which was calculated, in a less sophisticated way, by assuming every square metre of the country is covered with turbines.

Figure 3.2 on Page 19 does give a breakdown of this potential into different land cover types, but the data are presented only in the form of a chart, there being no accompanying table of numbers, and refer to 'unrestricted' technical potential, i.e. before the Natura 2000 sites and areas not windy enough to be 'competitive' have been removed. A similar graph for the 'restricted' potential is not given.

However, the EEA has released, in response to a user request, the spreadsheet from which the charts were plotted. This is available at:

http://community.eea.europa.eu/home/environmental-topics/energy/Wind_FiguresandTables_29April.xls/view

The data are shown in Table 4.5 on page 15. The following features stand out from this table:

- It appears to be suggesting that some countries should build wind turbines on glaciers, in marshes and in inland water bodies such as lakes! Well if you can build them offshore it must be a doddle to build them in a lake.
- The UK's total technical potential, $4,499TWh/y$, is even closer to the figure calculated by Professor MacKay for the same quantity, which confirms that this really does correspond to the case of covering every m^2 of the country with turbines.
- A more sensible estimate for the UK would be to limit ourselves to that part of the agricultural land that can have turbines on it and still be farmed, so as to avoid affecting food production. This could be done, for example, by planting them along field boundaries or the edges of roads. I have no idea what this would be, however. If it were, say, 10% of the area, then that would give us $127TWh/y$.

I'm therefore going to take $\boxed{127TWh/y}$ as the conclusion from EEA 2009.

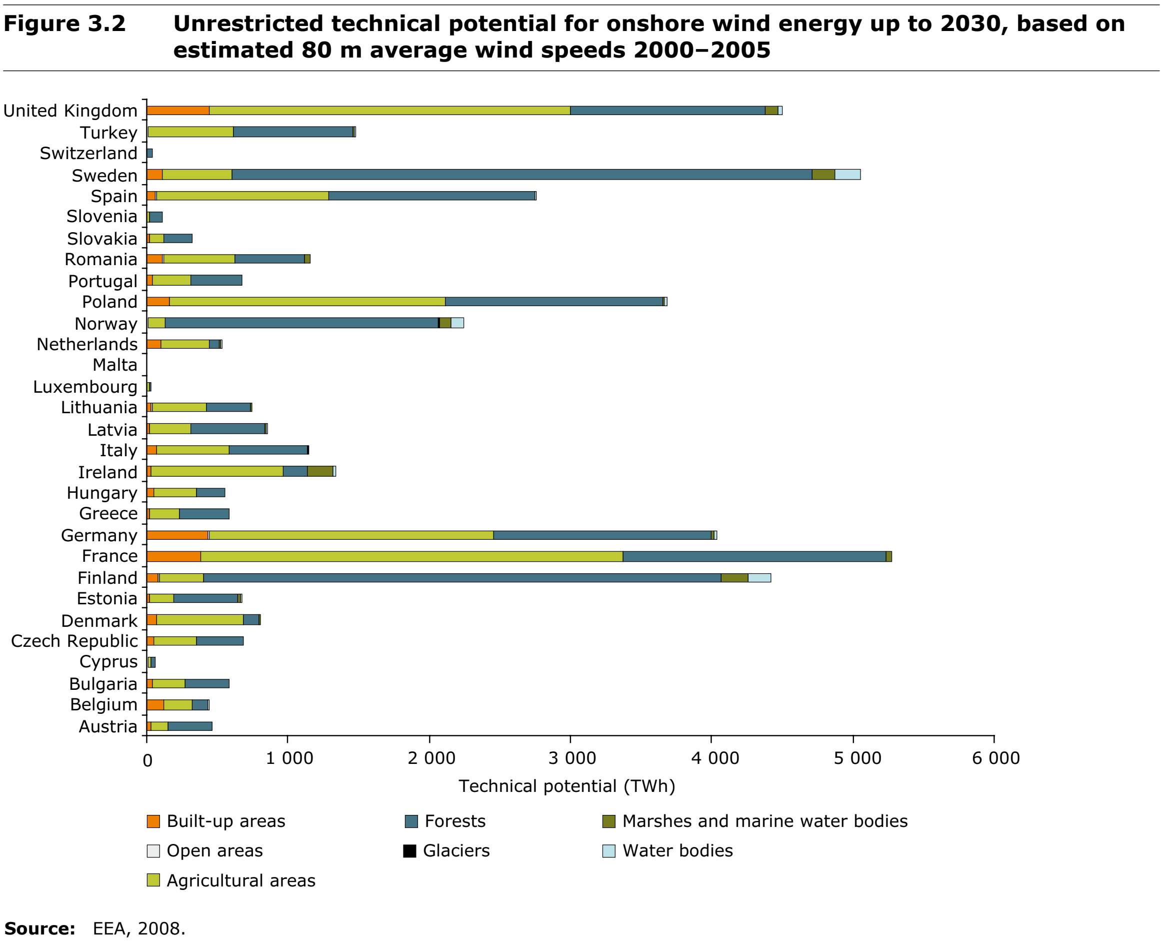


Figure 4.1: Unrestricted technical potential by land cover type (from [23] Page 19, Figure 3.2).

4.10 UK Wind Energy Database

This contains data from DECC's renewable energy planning database, but is hosted by RenewableUK. Though the rationale for doing so is not obvious, DECC allows RenewableUK to restrict access to these data so that only their members can see them. However, they do put summary statistics on public view. These headline figures on 27 April 2015 are shown in Table 4.6 on the next page.

This means that if all the projects in the table get built and become operational, the annual energy production would be:

Onshore

$$
\begin{aligned}
AEP &= \left(\frac{25.74}{100}\right) \times 8760 \times 22,329.845 \\
&= 87.6 \times 25.74 \times 22,329.845 \\
&= 50,349,870.4
\end{aligned}
$$

Offshore

$$
\begin{aligned}
AEP &= \left(\frac{33.56}{100}\right) \times 8760 \times 21,935.5 \\
&= 87.6 \times 33.56 \times 21,935.5 \\
&= 64,487,211.3
\end{aligned}
$$

Table 4.5: Data from Figure 3.2 of the EEA report

	Built-up areas	Open areas	Agricultural areas	Forests	Glaciers	Marshes and marine water bodies	Water bodies	Total
Austria	26.96	0.22	128.05	307.09	1.66	1.34	0.86	466.18
Belgium	116.35	1.04	208.15	110.43		1.69	0.74	438.39
Bulgaria	42.05	0.78	231.63	310.33		1.12	1.17	587.08
Cyprus	6.40	0.20	25.44	27.32		0.07	0.03	59.45
Czech Republic	53.96	1.18	292.33	337.71		0.55	1.58	687.31
Denmark	74.17	0.80	606.59	110.00		12.40	3.97	807.94
Estonia	16.32	1.16	178.58	444.21		19.49	17.80	677.57
Finland	84.46	1.93	321.28	3,657.09		189.32	170.41	4,424.49
France	379.90	6.66	2,985.38	1,859.35	0.41	39.21	8.68	5,279.59
Germany	433.35	9.39	2,017.27	1,535.08		22.61	16.76	4,034.46
Greece	17.19	1.38	208.90	357.57		1.78	0.34	587.16
Hungary	54.23	0.45	300.23	194.62		4.79	2.40	556.71
Ireland	33.26	1.78	932.59	172.16		181.74	17.26	1,338.78
Italy	73.30	1.73	510.75	556.62	1.77	6.38	1.13	1,151.68
Latvia	15.63	0.36	296.38	520.58		15.05	6.35	854.35
Lithuania	34.73	0.70	392.38	307.84		5.45	5.20	746.30
Luxembourg	3.19	0.06	12.73	13.53		0.01	0.03	29.54
Malta	2.45	0.08	3.16	0.91		0.01	0.00	6.62
Netherlands	96.19	1.78	349.96	66.80		11.54	7.39	533.66
Norway	9.38	0.00	119.61	1,932.88	7.83	88.34	90.85	2,248.89
Poland	159.84	3.76	1,952.79	1,533.01		13.84	23.78	3,687.01
Portugal	36.36	1.25	276.11	360.16		2.44	0.73	677.05
Romania	115.69	0.69	511.40	485.97		39.40	6.99	1,160.14
Slovakia	24.66	0.15	99.60	198.04		0.35	0.37	323.17
Slovenia	3.00	0.03	20.58	82.60		0.12	0.03	106.36
Spain	65.10	3.88	1,224.54	1,449.86	0.01	8.23	4.36	2,755.98
Sweden	109.75	1.36	488.05	4,115.07	0.47	157.34	186.67	5,058.71
Switzerland	0.56	0.00	2.08	37.09	2.31	0.01	0.24	42.29
Turkey	5.30	0.00	610.32	849.08		0.07	10.10	1,474.87
United Kingdom	438.11	9.74	2,550.22	1,377.96		96.09	26.90	4,499.02
Total	**2,531.82**	**52.54**	**17,857.06**	**23,310.97**	**14.48**	**920.78**	**613.09**	**45,300.74**

Table 4.6: Data from UKWED, downloaded 27 April 2015

	Onshore		Offshore		Total Capacity (MW)
	No of projects	Capacity (MW)	No of projects	Capacity (MW)	
In Planning	534	7,150.94	3	5,170	12,320.94
Consented	1,046	5,564.24	17	11,711.4	17,275.64
Under Construction	103	1,530.365	3	1,005	2,535.365
Operational	708	8,084.3	24	4,049.1	12,133.4
Total	**2,391**	**22,329.845**	**47**	**21,935.5**	**44,265.345**
Load factor	25.74%		33.56%		

Total

$$50,349,870.4 + 64,487,211.3 = 114,837,082$$

or 114.8TWh/y, of which, 50.35TWh/y is from onshore and 64.5TWh/y if from offshore. That means that if all the onshore projects currently consented or in planning get built, then the onshore capacity will have hit the 50TWh/y figure quoted in some of the above reports as the practical potential. Given that this has been achieved with relatively little effort suggests that the real potential is considerably more than this.

4.11 Summary & conclusion

Table 4.7 summarises the results of the studies described above.

Table 4.7: Onshore wind summary of studies

Study	'Accessible' resource (TWh/y)
DTI wind energy fact sheet No 8	50
Leithead 2007	50
EEA 2009 (sensible subset)[a]	127
Brocklehurst 1997	317.854[b]
ETSU 1999	317.854
ETSU 1994	340
MacKay 2008	470
Grubb & Meyer 1993	750

[a] Derived by taking 10% of the output of the land area described as 'agricultural' in the EEA report.
[b] Excluding places where the annual mean wind speed at a height of $45m$ above the ground is less than $7m/s$.

Discarding the highest and lowest values gives a range of:

$$\boxed{127 - 470TWh/y}$$

5 Offshore wind

5.1 ETSU 1994 [4]

This says (page 46)

> Accessible Offshore Resource
>
> Taking workable water depth constraints into account, the accessible resource is estimated to be about $\boxed{380TWh/year}$.

5.2 ETSU 1999

Only the 'practicable' resource is estimated. No figures are presented for the 'accessible', other than the word 'vast'.

Table 5.1: Offshore wind practicable resource (from ETSU 1999 Section 4.1 Table 6)

Water Depth (m)	Resource (TWh/year) at Distance (km)			Totals
	0 - 10	10 - 20	20 - 30	
0 - 10	14.39	1.45	0.12	15.95
10 - 20	12.23	8.95	3.70	24.88
20 - 30	15.52	14.26	6.12	35.89
30 - 40	6.58	10.94	5.93	23.45
Totals	48.73	35.59	15.86	100.18

5.3 DTI Wind Energy Fact Sheet 1—Offshore wind energy [24]

Says:

> The UK's offshore wind resource is vast, with the potential to provide more than the UK's current demand for electricity.

and

> The accessible offshore wind resource is estimated to be many times more than the UK electricity demand of about $300 TWh$ per year. This estimate only takes into account water depth and not any of the other constraints.
>
> However, certainly in the short to medium term, it is not practically possible to realise all of this resource. A more realistic figure is estimated to be $100 TWh$ per year. This lower figure takes into account reasonable distances from the shore, water depth, type of seabed and the existing uses of the possible areas.

5.4 CA-OWEE 2001 [25]

'Concerted Action on Offshore Wine Energy in Europe' was a large multi-partner EU project whose aim was to '…define the current state of the art of offshore wind energy in Europe through gathering and evaluation of information from across Europe and to disseminate the resulting knowledge to all interested, in order to help stimulate the development of the industry'. The project included a resource assessment the results of which are presented in Table 5.2.

Table 5.2: EU offshore wind potential (Table 4.2 on page 4-2 of CAOWEE 2001 [25])

Country	Resource estimate		Target installation		Comments	Reference
	MW	TWh/y	MW	year		
BE	1200	4	200	2004	Two projects of 100 MW have been announced.	www.electrabel.com
DK	8000	26	4000	2030	Additional 4000 MW water depth > 20 m Exploitable resource 83-287 TWh/y	[1, 2, 3]
FI	6000	20	0			
FR	13000	44	0		EED studies indicate potential in four areas of 9125 MW or 30.1 TWh.	[2]
D	13000	45	0			[2]
GR	1500	5	0			[2]
EI	3300	11	1250	2010?	Water depth< 20 m, Min distance 5km, 32% of nat. electricity	
I	3000	10	1000	2030		[2, 4]
NL	10000	33	1250	2020	~11% of national electricity consumption	[5, 6]
PL	600	2-3	0		Technical potential is 11 PJ offshore wind energy. Two projects have consents and two more are pending.	BAPE
PT	0	0	0			
ES	2000	7	0		Two projects in planning, monitoring at one	[6]
SE	7000	22.5	650	2005	Many projects at planning stage	[2, 7]
UK	70000	230-334	2600	2010	Planned 2% of UK supply by 2010	[7]
	138600	459.5 - 564.5	10950			

Thus the potential for the UK is $\boxed{230-334 TWh/y}$.

5.5 MacKay 2008

MacKay assumes that the available sea area is:

- shallow ($0-25m$ deep): $40,000 km^2$ (roughly twice the size of Wales) and
- deep area ($25-50m$ deep): $80,000 km^2$ (roughly the size of Scotland),

but that two thirds would be unavailable due to competing uses of the sea, leaving a total of $40,000 km^2$ in which turbines could be deployed. He next assumes that the annual average power output per unit area of sea surface is

$3W/m^2$. Consequently the total annual average power is:

$$
\begin{aligned}
Annual\,average\,power &= 40 \times 10^3\,(km)^2 \times 3W/m^2 \\
&= 40 \times 10^3 \times \left(10^3 m\right)^2 \times 3W/m^2 \\
&= 40 \times 10^3 \times \left(10^3\right)^2 m^2 \times 3W/m^2 \\
&= 40 \times 10^3 \times 10^6 \times 3W \\
&= 40 \times 3 \times 10^9 W \\
&= 120GW \\
&= 120GW \times 8760h/y \\
&= 120 \times 8760GWh/y \\
&= 1,051,200GWh/y \\
&= 1,051.2TWh/y
\end{aligned}
$$

To convert this into Professor MacKay's preferred unit of $kWh/person/day$ first divide by 59.5 million people and then divide by 365 days per year.

$$
\begin{aligned}
Power &= \frac{1,051.2TWh/y}{59.5 \times 10^6 people \times 365 days/y} \\
&= \frac{1,051.2 \times 10^{12} Wh/y}{59.5 \times 10^6 people \times 365 days/y} \\
&= \frac{1,051.2 \times 10^3 kWh/y}{59.5 people \times 365 days/y} \\
&= \frac{1,051.2 \times 10^3}{59.5 \times 365} kWh/person/day \\
&= 48.403 kWh/person/day
\end{aligned}
$$

which agrees with Professor MacKay's figure of $16kWh/person/day$ for shallow offshore wind plus $32kWh/person/day$ for deep offshore wind.

5.6 EEA 2009

As with onshore wind, this report gives a breakdown by country of 'unrestricted technical potential' only in the form of a graph, but the EEA has released a spreadsheet containing the numbers from which the graph was plotted. These are shown in Table 5.3 on the facing page. This gives the 'unrestricted technical potential' for the UK as $4793TWh/y$. The report then goes on to discuss constraints on development. Unlike onshore, where constrains were relatively minor, offshore roughly 90% of the sea area is excluded. The fraction of the sea area available for development after constraints are taken into account are given in Table 5.4 on the next page. Applying these percentages to the UK data in Table 5.3 gives:

$$1460 \times 4\% + 1043 \times 10\% + 475 \times 10\% + 1815 \times 25\% = 663.95TWh/y$$

5.7 Summary and conclusions

Table 5.5 on page 20 lists the bottom lines of the above studies in ascending order of size. Discarding the lowest and highest estimates gives a range of:

$$\boxed{200 - 663TWh/y}$$

6 Solar

PV and solar thermal are mutually exclusive in that you can't have both on the same bit of roof, although in the future there might be water-cooled PV panels in which the cooling water is one of the heat sources for a building, possibly in combination with a heat pump. This mutual exclusivity means that, for the purposes of this analysis, we need to choose one or the other. I have chosen PV.

Table 5.3: Data from EEA 2009, Figure 3.5

	< 10 km	10-30 km	30-50 km	>50 km	Total
Austria	0	0	0	0	0
Belgium	10	106	109	27	251
Bulgaria	41	119	40	0	199
Cyprus	18	2	7	0	27
Czech Republic	0	0	0	0	0
Denmark	697	655	245	1119	2715
Estonia	269	327	202	8	806
Finland	378	624	312	175	1489
France	543	792	427	199	1961
Germany	310	257	162	981	1711
Greece	354	307	79	8	748
Hungary	0	0	0	0	0
Ireland	490	392	101	118	1101
Italy	265	462	223	45	996
Latvia	145	255	129	12	541
Lithuania	29	42	15	2	88
Luxembourg	0	0	0	0	0
Malta	5	1	0	0	6
Netherlands	183	342	221	1654	2400
Norway	770	312	81	760	1923
Poland	127	198	107	52	484
Portugal	96	153	70	9	328
Romania	44	79	34	1	159
Slovakia	0	0	0	0	0
Slovenia	0	1	0	0	2
Spain	306	155	59	4	524
Sweden	636	431	170	292	1528
Switzerland	0	0	0	0	0
Turkey	328	92	17	0	437
United Kingdom	1460	1043	475	1815	4793

Table 5.4: EEA 2009 offshore wind constrained potential

Distance from shore (km)	Fraction of area that could be developed
$0-10$	4%
$10-30$	10%
$30-50$	10%
>50	25%

6.1 ETSU 1994

This says

> A detailed assessment of of the UK Accessible Resource from building-mounted systems has been carried out, taking into account shading, unsuitable buildings, architectural requirements and other constraints. This indicates a resource of up to $200 TWh/y$, in the short term and up to $\boxed{360 TWh/y}$ in the long term (2020). This study included all available surfaces in all orientations, but for simplicity, the resource and cost assessments in this module only included south facing surfaces.
>
> Table 2 below [Table 6.1 on the next page of this paper] summarises the current best estimates for the Accessible Resource for systems likely to produce electricity under 10p/kWh. The assumptions behind these figures are explained in sections E and F.

Table 5.5: Offshore wind summary of studies

Study	Practical resource (TWh/y)
DTI wind energy fact sheet No 1	100
Leithead 2007	100
ETSU 1999	100.18
Grubb and Meyer	200
CA-OWEE 2001	$230-334$
ETSU 1994	380
EEA 2009	663.95
MacKay 2008	1051

Table 6.1: Accessible Resource in the UK (<10p/kWh future long term resource)

Discount rate	England and Wales	Scotland	Northern Ireland	UK
8%	76	6.5	1.5	84
15%	4.0	0.2	0.0	4.2

I think that the figures of 200TWh/y and 360TWh per year refer to all roof orientations—i.e. not just south facing, while the figures in Table 6.1 refer to south facing roofs only. The report does not explain how the authors estimated the size of the subset of the resource for which the cost of energy $< 10p/kWh$, but the result quoted in Table 6.1 is big enough to include all south-facing roofs given the other stated assumptions.

6.2 DTI 1994

This says:

> The horizontal insolation[3] (averaged over the year) in the UK ranges from 2.2 kWh/sq.m/day in northern Scotland to 3.0 kWh/sq.m/day in southern England. However, the efficiency of ... current commercial modules ranges between 5% and 16%, ...

It gives the following figures:

Table 6.2: UK Photovoltaic resource ([5], Page B19, Table 2)

Accessible Resource (TWh/y) at < 10p/kWh (1992), 8% discount rate	84
Maximum Practicable Resource (TWh/y) in 2005 at < 10p/kWh (1992), 8% discount rate	0.004 to 0.08

The first row of this table is clearly from ETSU 1994, but there is no indication where the figures in the 2nd row are from or how they are derived.

6.3 ETSU 1999

This says:

> The resource is calculated using a relatively complex model and applying PV to all surfaces, e.g. roofs and all orientations of facades.
>
> **General**
>
> - Solar radiation for UK assumed to be equivalent to that at Kew, London ($1000kWh/m^2/year$ on a horizontal surface).
> - Number of buildings increases into the future using assumed new-build rate ($0.57\% - 2.43\%$, variable depending on building sector).

[3] This hideous bit of jargon is a contraction of the much preferable '*in*cident *sol*ar radi*ation*'. Not to be confused with 'ins*u*lation', which is something completely different.

- PV efficiency, inverter efficiency, PV cost/m^2, inverter cost and wiring cost gradually improve into the future (see Table 4 and Section 4.2 for costs).

Table 4: General PV Cost Trends

	1997	**2005**	**2025**
PV efficiency (%)	6–12.5	10.2–13.6	12–15
Inverter efficiency (%)	90	92	95
PV lifetime (years)	25	25	25

Domestic

- Number of domestic properties based on number of households ($\approx$ 24.6 million), with percentage taken off (18%) for number of flats.
- Average pitch roof area assumed for dwellings ($\approx 70m^2$).
- All domestic roof area has a pitch between 20° and 45° .
- Fraction of roof area assumed to be suitable for PV ($\approx$ 90%).
- Orientation distribution of properties assumed to be equal among eight defined orientations.
- An allowance made for shading (25%).
- An inverter size of $2-5kW$.
- An avoided cost of conventional roofing taken into account for new-build ($0-15£/m^2$).

Non-Domestic

- Non-domestic stock divided into sectors corresponding to types of use.
- Both available roof area and wall area included.
- Wall areas and roof areas assumed to be related to floor area statistics.
- A fraction assumed for areas which are not doors, windows, ground floor, under overhang, chimneys, aerials or rooflights ($\approx$ 60%).
- An allowance made for shading ($25-40$%).
- A distribution of roof pitches assumed.
- Assumptions made as to the construction type appropriate for PV cladding in buildings pre- 1994 and buildings post-1994 ($\approx$ 56% and $\approx$ 85% respectively).
- Avoided costs of roofing/cladding taken into account for new-build ($0-122£/m^2$).

Based on the above assumptions, the maximum practicable resource in 2025 is $\boxed{266TWh/year}$. The maximum practicable resource includes PV applied to all orientations. A substantial proportion of this resource will be at relatively much higher cost due to lower levels of received sunlight eg for north-facing surfaces.

6.4 MacKay 2008

Chapter 6 says:

> The power of raw sunshine at midday on a cloudless day is $1000W$ per square metre. That's $1000W$ per m^2 of area oriented towards the sun, not per m^2 of land area. To get the power per m^2 of land area in Britain, we must make several corrections. We need to compensate for the tilt between the sun and the land, which reduces the intensity of midday sun to about 60% of its value at the equator (figure 6.1). We also lose out because it is not midday all the time. On a cloud-free day in March or September, the ratio of the average intensity to the midday intensity is about 32%. Finally, we lose power because of cloud cover. In a typical UK location the sun shines during just 34% of daylight hours.
>
> The combined effect of these three factors and the additional complication of the wobble of the seasons is that the average raw power of sunshine per square metre of south-facing roof in Britain is roughly $110W/m^2$, and the average raw power of sunshine per square metre of flat ground is roughly $100W/m^2$.

> Photovoltaic (PV) panels convert sunlight into electricity. Typical solar panels have an efficiency of about 10%; expensive ones perform at 20%. (Fundamental physical laws limit the efficiency of photovoltaic systems to at best 60% with perfect concentrating mirrors or lenses, and 45% without concentration. A mass-produced device with efficiency greater than 30% would be quite remarkable.) The average power delivered by south-facing 20%-efficient photovoltaic panels in Britain would be
>
> $$20\% \times 110W/m^2 = 22W/m^2$$

he then says that

> . . . the area of all south-facing roofs is $10m^2$ per person, . . .
>
> I estimated the area of south-facing roof per person by taking the area of land covered by buildings per person ($48m^2$ in England – table I.6), multiplying by 1/4 to get the south- facing fraction, and bumping the area up by 40% to allow for roof tilt. This gives $16m^2$ per person. Panels usually come in inconvenient rectangles so some fraction of roof will be left showing; hence $10m^2$ of panels.

Table I.6 is reproduced in Table 6.3. $48m^2/person$ multiplied by $59.6 \times 10^6 people$ is equal to $2856 \times 10^6 m = 2856km^2$. This agrees to within rounding error with the figure of $2837km^2$ used by UKPV and quoted in Table 6.5 on the facing page.

Multiplying $22W/m^2$ by $10m^2/person$ by $59.5 \times 10^6 people$ by $8760hours/year$ gives $11466840 \times 10^7 = 114.7 \times 10^{12} Wh/y$ or

$$\boxed{115TWh/y}$$

.

Table 6.3: Data on areas from MacKay 2009 [15]

I — Quick reference 333

Land use	area per person (m^2)	percentage
– domestic buildings	30	1.1
– domestic gardens	114	4.3
– other buildings	18	0.66
– roads	60	2.2
– railways	3.6	0.13
– paths	2.9	0.11
– greenspace	2335	87.5
– water	69	2.6
– other land uses	37	1.4
Total	2670	100

Table I.6. Land areas, in England, devoted to different uses. Source: Generalized Land Use Database Statistics for England 2005. [3b7zdf]

6.5 2020 A vision for UK PV [26]

Most recent references to the UK PV potential derive from this 2009 study by the increasingly inaccurately named British Photovoltaic Manufacturers Association (now re-branded, for obvious reasons, as just the British Photovoltaic Association). This says:

> The calculation shown in Figure 1 below sets out our view of absolute potential, based on the 4,000 available km^2 of roofs and facades on UK buildings[4]. Additionally, rather than use theoretical PV efficiencies we have used outputs observed in field trials, and we have de-rated this output where required to allow for orientation of PV (i.e., not south facing, or not angled optimally towards the sun).

Table 6.4 reproduces the results, and Table 6.5 lists some of the data sources and assumptions used.

[4] DCLG, "Generalised Land Use Database Statistics for England", 2007

Table 6.4: UK PV potential, from [26]

	Area km^2	GWp	Adjustment for pitch and azimuth	TWh/yr	% of UK electricity consumption
South facing domestic roofs	549	92	100%	78	
East or west facing domestic roofs	1,099	183	82%	127	
North facing domestic roofs	549	92	58%	45	
Total domestic roofs	2,198	366		250	
South facing other roofs	259	43	88%	32	
East or west facing other roofs	519	86	88%	64	
North facing other roofs	259	43	88%	32	
Total other roofs	1,037	173		129	
South facing façades	299	50	71%	30	
East or west facing façades	598	100	50%	42	
North facing façades	299	50	20%	9	
Total façades	1,197	199		81	
Total all building-mounted	4,432	739		460	116%
Subtotal - south facing only	1,106	185		140	35%
Subtotal - south, east west facing only	3,324	554		374	94%

Table 6.5: Data sources and assumptions from [26]

1. Available building space			
	England	UK	Source:
2007 population, m	51.1	61.0	National Statistics
Total land area km2		244,000	
Domestic buildings km2	1,508	1,800	Generalised land use database 2005
Other buildings km2	869	1,037	
Total buildings km2	2,377	2,838	
Ratio pitched roof area : plan area		1.2	Trigonometry
Domestic roofs km2		2,198	
Other roofs km2		1,037	
Total roofs km2		3,235	
Ratio façade area : roof area		0.37	IEA 2002
Domestic façades km2		813	
Other façades km2		384	
Total façades km2		1,197	

6.5.1 Observations

1. The ratio between the area of a pitched roof to the plan area of the building is stated to be 1.2. The source for this is given as 'trigonometry'. I think that this means that the roof angle is 45° and that 85% of the roof is covered by PV panels. This would mean that the area of the roof per unit floor area is $1/\cos(45°) = \sqrt{2} = 1.4142$, 85% of which is $1.4142 \times 0.85 = 1.2021$.

2. 'South facing' is taken to mean that the roof faces anywhere in the 90° quadrant that extends from SW to SE, and similarly for the other three directions.

3. A quarter of all roofs is assumed to fall in each of the four quadrants. This means that a quadrant only includes half the number of roofs that have a side facing into that quadrant. This has the effect of cancelling out the double counting that would result from counting the whole area of the roof.

Table 6.6: Solar PV summary of studies

Study	Practical resource (TWh/y)	
	South facing roofs only	All roof orientations
ETSU 1999	not stated[a]	266
ETSU 1994	84	360
MacKay 2008	115	not stated[a]
UKPVMA	140	460

[a] In the absence of information that would enable a more accurate calcualtion, a reasonable estimate is that the 'all roofs' figure is roughly 3.3 times as large as the 'south facing only' figure.

6.6 Summary and conclusions

Table 6.6 summarises the results of the studies discussed in this section. There are not enough results to discard the lowest and highest estimates and still have more than one number left. I have therefore decided to just take the largest and the smallest:

South facing roofs

$$84 - 140 TWh/y$$

All roof orientations

$$266 - 460 TWh/y$$

7 Hydro

7.1 Large hydro

Table 7.1 shows UK hydro capacity and generation in 2013. The UK has no more sites suitable for large hydro schemes

Table 7.1: UK hydro capacity and generation in 2013 (from DUKES 2014, Table 6.4)

	Installed capacity (MW)	Generation (GWh/y)	$(GWh/y)/MW$
Large	1471	4026	2.7369
Small	222	672	3.0270
Total	1693	4698	2.7750

so the current generation *is* the potential. The potential for large hydro is therefore:

$$4.0 TWh/y$$

The annual output will depend on the amount of rainfall, of course, but for this analysis we want a single number.

7.2 Small hydro

There is still plenty of unexploited small hydro resource left. The studies listed below try to estimate it.

7.3 ETSU-SSH-4063 (1989)—a.k.a 'Salford Hydro Study' [27]

This was the first ever comprehensive survey of the small hydro resource in the UK. It was done by Salford Civil Engineering Ltd (SCEL, part of Salford University) under contract to the Department of Energy beginning in 1987 and reporting in 1989. It was published in three volumes in hard copy but has never been made available electronically on the internet. As a service to my readers, I have put a scanned copy on my website at the following address:

Volume 1: http://www.howardrudd.net/files/ETSU-SSH-4063-P1.pdf

Volume 2: http://www.howardrudd.net/files/ETSU-SSH-4063-P2.pdf

Volume 3: http://www.howardrudd.net/files/ETSU-SSH-4063-P3.pdf

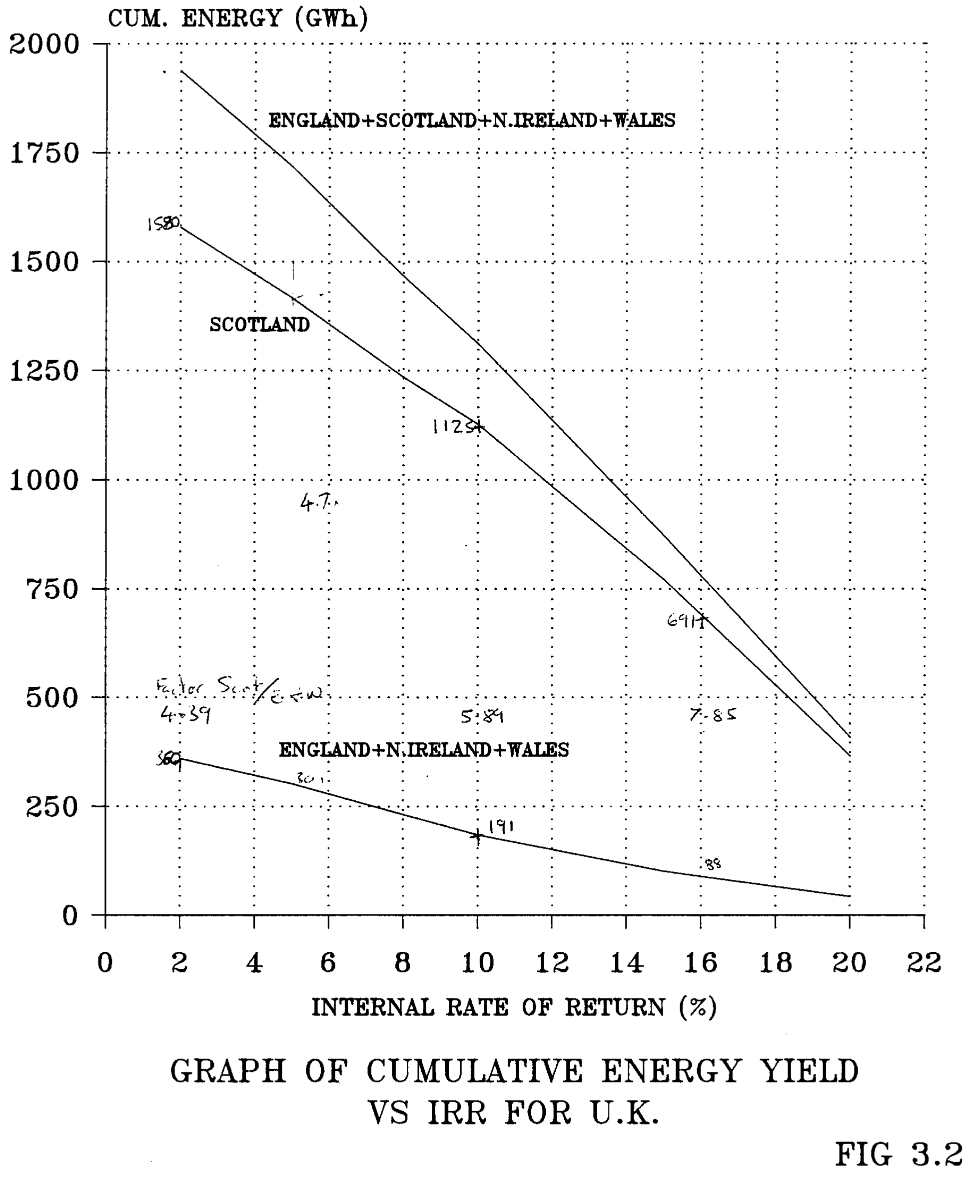
The British Hydropower Association has put on its website pdf printouts of four spreadsheets—one for England and Wales, one for Northern Ireland, one for Scotland and one for rejected sites—that were produced as part of this study. They do not say where these spreadsheets came from but I think they must have been on a floppy disk distributed with the report. They can be found here:

http://www.british-hydro.org/hydro_in_the_uk/uk_hydro_resource/1989_salford_study.html

The study surveyed over 1400 sites with a potential capacity of $\geqslant 25kW$ in England, Wales, Scotland and Northern Ireland. The majority of sites were in Scotland. It found that the resource available at $\geqslant$ 5% IRR is $1717GWh/y$ from $411MW$ of capacity and at $\geqslant$ 10% is $1312GWh/y$ from $322MW$. This gives a rough annual energy production per MW of $4.1GWh/y/MW$.

Figure 7.1 shows the energy yield as a function of IRR. Although not explicitly stated in the report, measuring pixels

Figure 7.1: Energy yield from small hydro in the UK (from Salford Study [27])



on this graph suggests that the available resource at $\geqslant$ 2% IRR is $1937GWh/y$. Table 7.2 on the following page gives the geographical distribution of the resource.

Table 7.2: Geographical distribution of potential capacity (kW) (from Salford Study [27])

	$IRR \geqslant 5\%$			$IRR \geqslant 10\%$		
	Capacity (kW)	Generation (GWh/y)	$(GWh/y)/MW$	Capacity (kW)	Generation (GWh/y)	$(GWh/y)/MW$
Scotland	350,240			285,937		
England	33,700			19,219		
Wales	21,337			14,890		
Northern Ireland	5,723			2,183		
Total	411,000	1717	4.1776	322,229	1312	4.0716

7.4 ETSU 1994

The unexploited Accessible Resource for small scale hydro in the UK might be in the region of 400 to 700MW. An additional estimated Accessible Resource of around 500MW exists at sites with hydraulic heads of less than 3m, but at present exploitation of this is not likely to be economic.

Table 7.3: 'Estimates of the hydro power Accessible Resource for the UK at less than 10p/kWh' (from ETSU 1994 [4] page 63)

Accessible Resource Measure (TWh/year)	Discount Rate	England & Wales	Scotland	Northern Ireland	UK
Small-scale	8%	0.45	3.4	0.05	3.9
	15%	0.45	3.1	0.05	3.6
Large-scale	8%	0.3	6.6	0	6.9
	15%	0.3	4.5	0	4.8

The figure for large hydro, 4.8TWh/y is 20% larger than the actual generation by large hydro in 2013. They might have assumed some further large hydro potential above that that already exists, or they might have assumed higher levels of rainfall.

7.5 DTI 1994

Most of the large-scale hydro capacity in the UK is installed in Scotland (1.1GW), with a smaller amount in Wales (140MW). The small scale sites comprise about 58MW in Scotland and 20MW in England and Wales. Hydro power accounts for about 2% of the total installed generating capacity in the UK. An additional category is low head hydro (less than 3m which is also categorised as small scale).

Within the UK there is little scope for further development of large scale hydro because of the cost and concerns about its environmental impact. However, the two scales of technology can extract energy from a rainfall catchment area in different ways. There is therefore a potential for the further development of small scale hydro for which approximately 80% of the unexploited resource is in Scotland.

Table 7.4: 'UK Hydro Resource - existing schemes provide the bulk of this resource (see ref 3)', (from DTI 1994 [5] Page B8, Table 2).

	Accessible Resource (TWh/y) at < 10p/kWh (1992), 8% discount rate	Maximum Practicable Resource (TWh/y) in 2005 at < 10p/kWh (1992), 8% discount rate
Small scale hydro	3.9	3.9
Large scale hydro	6.9	3.9

7.6 ETSU 1999

The total hydro power resource for the UK is estimated at $40TWh/y$, or $13GW$ of installed capacity (this is based upon mean annual rainfall figures, land area and elevation data. However, studies of potential small hydro sites in the UK which take account of geographical and environmental constraints on potential sites indicate that the accessible resource is considerably less than this.

In Scotland, in addition to the existing large-scale capacity of $1.22GW$, there may be an unexploited accessible resource of up to $1GW$ or $\boxed{3TWh/year}$. This resource would require reservoir storage and its development is therefore likely to be limited by environmental constraints. The unexploited accessible resource in Wales has not been quantified but is thought to be small because of environmental considerations. There are no large-scale resources in England or Northern Ireland.

The remaining practically feasible, UK small hydro resource which might be commercially attractive (including those sites currently contracted under the NFFO, NI-NFFO and SRO) is estimated at between $110MW$ and $40MW$ ($< 5p/kWh$ unit generation cost at 8% and 15% discount rate over 15 years respectively). Using the same economic parameters, the remaining resource at $< 10p/kWh$ is between $300MW$ and $550MW$.

7.7 Forrest et al 2008 [28]

This study was undertaken for the hydropower subgroup of FREDS[5]. It was carried out using a GIS computer model called 'hydrobot':

> Hydrobot was devised in 2006 and applied to the catchment of the North and South Esk near Edinburgh, as part of an award-winning MSc dissertation for the University of Edinburgh.

Table 7.5 gives the results.

Table 7.5: Scottish hydro resource (from Forrest et al [28], Table 1)

Total number of schemes	Total potential power (MW)	Total potential annual energy (MWh)	Financially viable schemes	Financially viable power (MW)	Financially viable annual energy (MWh)
36,252	2,593	10,644,403 (capacity factor 47%)	1,019	657	2,766,682 (capacity factor 48%)

"Total values include all technically possible schemes in Scotland modelled by Hydrobot, including those with a negative NPV. Financially viable values in include schemes with a positive NPV after the recovery period (25 years in baseline scenario)." "Baseline scenario" refers to the set of assumptions used in the calculations.

7.8 BHA & IT Power, 2010 [29]

This study is an update of the England and Wales part of the 1989 Salford study. The justification for updating it is that many sites that were excluded from the original survey are now likely to be viable because of increased levels of subsidy and improvements in technology. As well as reassessing the sites from the 1989 report, it also estimates, using a 'top down' methodology, capacity that was not even considered in the earlier report. The results are presented in terms of capacity, and not generation. Table 7.6 on the following page reproduces their results.

For England this is a five to six fold increase on the Salford study, and for Wales it is a two to three fold increase. The study expresses its results as power generation capacity (MW) not as annual energy production (GWh/y). We can get the latter by assuming a capacity factor. The following sources report typical capacity factors for hydro projects:

- DECC's guidance for small hydro developers [30], says: 'Hydro has a typical load factor of 35 to 40%'.
- The British Hydropower Association's mini-hydro guide [31] says 'The Capacity factor for most mini-hydro schemes would normally fall within the range 40% to 60%...'.
- The Wikipedia article on hydroelectricity [32] lists the average capacity factors of the top ten hydro generating countries. These range from 37% to 67%.

[5] Forum for Renewable Energy Development in Scotland.

Table 7.6: Results of 2010 England and Wales Hydropower Study

	Number of Sites	Lower MW	Upper MW
English Regions			
Anglian	126	4.92	13.37
North West	284	32.0	37.7
Midlands	157	18.0	32.4
Southern	36	1.1	2.6
South West	322	20.0	29.4
Thames	125	16.2	30.12
North East	318	27.33	39.81
England Total	1368	119.55	185.4
Wales Total	324	26.73	63.0
England & Wales	1692	146.28	248.4

- The plant reported in DUKES 2014 and reproduced in Table 7.1 on page 24 have a ratio of annual energy production to installed capacity of roughly $3GWh/y/MW$ equivalent to 34% capacity factor.
- The plant modelled in the studies surveyed here give:
  - Salford study: roughly $4.1GWh/y/MW$ equivalent to a capacity factor of $4.1/8.76 = 47\%$
  - Forrest et al: 47% to 48%

Of these, I think the best one to choose would be the figures from DUKES, as they represent actual results from real plant. Consequently, I'm going to go with 34%, equivalent to $3GWh/y/MW$ (which is a nice round number). This means that $146.28MW$ would generate $146.28 \times 3 = \boxed{438.84GWh/y}$ and $248.4MW$ would generate $248.4 \times 3 = \boxed{745.20GWh/y}$.

7.9 Summary and conclusions

Table 7.7: Summary of small hydro resource studies

	England & Wales		Scotland		UK	
	Capacity (MW)	AEP(TWh/y)	Capacity (MW)	AEP(TWh/y)	Capacity (MW)	AEP(TWh/y)
Salford study [a]	60.76 [b]		350.24		411	1.717
ETSU 1994	-	0.5 [b]	-	3.4	-	3.9
DTI 1994	-	-	-	-	-	3.9
ETSU 1999	-	-	-	3.0	-	-
Forrest 2008 [c]	-	-	657	2.77	-	3.52
BHA/IT Power [d]	146.28 to 248.4	0.44 to 0.75	-	-	-	

[a] $\geqslant$ 5% IRR
[b] includes Northern Ireland
[c] "financially viable", Scotland only
[d] England and Wales only

Discarding the lowest and highest estimates leaves us with one result, which is the one obtained by adding Forrest et al (for Scotland) to BHA/IT Power (for England and Wales). This is also the most recent estimate. It gives $3.52TWh/y$ for small hydro in the UK. Adding this to the $4TWh/y$ from large hydro and rounding to 1 decimal place gives:

$$\boxed{7.5TWh/y}$$

8 Tidal range

8.1 ETSU 1994

This says (Page 79):

> No estimate is available of the total Accessible Resource from all UK estuaries. However, if every reasonably practicable estuary with a mean spring tidal range exceeding 3.5m were to be employed for tidal power, the yield would be about $50TWh/y$, ... About nine tenths of this would be at eight larger sites (Severn, Dee, Mersey, Morecambe Bay, Solway Firth, Humber, Wash, Thames) ...

And

> At $17TWh/year$ the Severn Barrage, if built, would be by far the largest single renewable energy project ... in the world.

Table 8.1 presents the numbers.

Table 8.1: 'Accessible Resource in the UK available at a cost of under 10p/kWh (1992 prices)' (from ETSU 1994 [4])

Discount Rate	England & Wales	Scotland	Northern Ireland	UK
8%	$19TWh/y$	0	0	$19TWh/y$
15%	0	0	0	

8.2 DTI 1994

> The Severn barrage ... , providing about $17TWh/y$ of electricity, ... would make up the majority of the Accessible resource of $18.6TWh/y$ at less than $10p/kWh$ (1992 prices) using an 8% Discount Rate.

Table 8.2: 'UK tidal power resource' (Table 2, page B11 of DTI 1994 [5])

Accessible Resource (TWh/year) at less than 10p/kWh (1992). 8% discount rate.	Maximum Practicable Resource (TWh/year) in 2005 at less than 10p/kWh (1992). 8% discount rate.
19	1.6

8.3 ETSU 1999

This did not give an estimate for this technology.

8.4 Boyle 2004

Page 223:

> In theory, the exploitable potential, assuming that every practical UK scheme was developed, could rise to approximately $53TWh\,y^{-1}$, or around 14% of UK electricity generation in 2002. Approximately nine-tenths of this potential ($48TWh\,y^{-1}$) lies in eight large sites, each offering between $1TWh\,y^{-1}$ and $17TWh\,y^{-1}$, while one tenth relates to 34 small sites each providing somewhere in the range $20-150GWh\,y^{-1}$

Table 8.3 on the next page shows the numbers presented in Table 6.4 on page 224. These data are stated to be from Baker 1986

	Range (m)	length (m)	Capacity (MW)	output (GWh/y)
Severn – outer line	6.0	20000	12000	19700
Severn – inner line	7.0	17000	7200	12900
Solway firth	5.5	30000	5580	10050
Morecambe bay	6.3	16600	3040	5400
Wash	4.45	19600	2760	4690
Humber	4.1	8300	1200	2010
Thames	4.2	9000	1120	1370
Dee	5.95	9500	800	1250
Mersey	6.45	1750	620	1320
Milford Haven	4.5	1150	96	180
Cromarty Firth	2.75	1350	47	100
Loch Broom	3.15	500	29	42
Loch Etive	1.95	350	28	55
Padstow	4.75	550	28	55
Langstone Harbour	3.13	550	24	53
Dovey	2.90	1300	20	45
Hamford Water	3.0	3200	20	38

Table 8.3: 'An early assessment of some potential tidal barrage sites in the UK' [Table 6.4 of [14]]

8.5 Baker 1991 [33]

Figure 8.1 shows a supply curve for tidal barrage projects in the UK. No explicit numbers were given, but it does show that the non-Severn projects can add up to as much as the Severn.

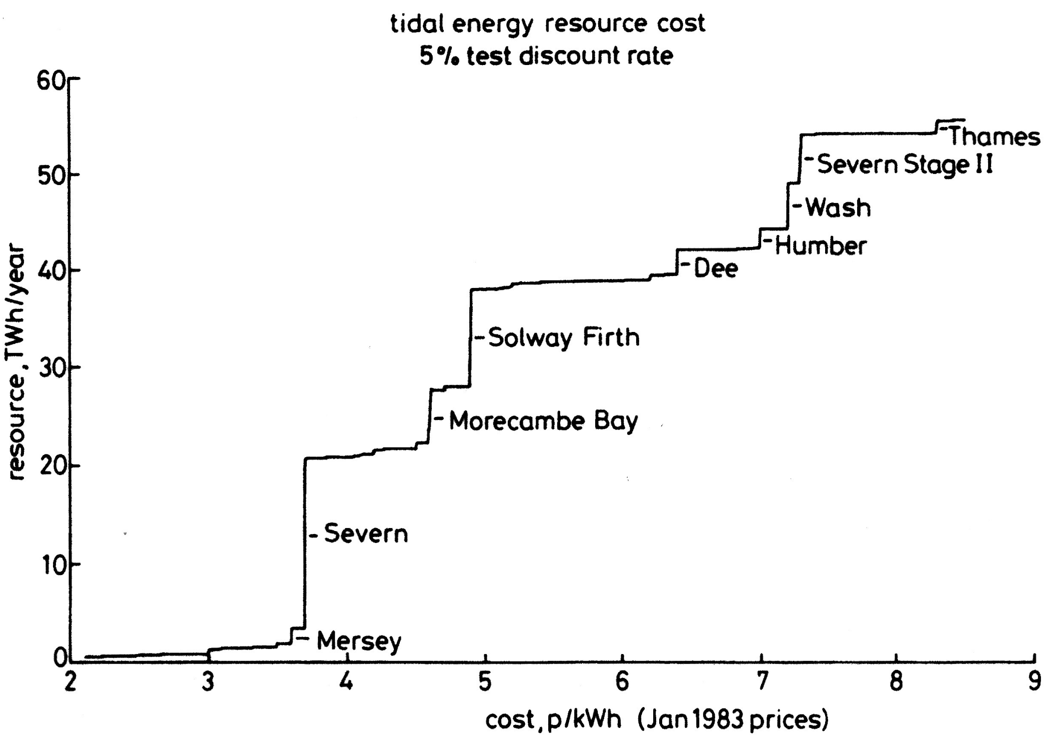


Fig. 12.38 Cumulative UK tidal energy/cost (1983 prices)

Figure 8.1: UK tidal energy supply curve (from Baker 1991 [33])

8.6 Sustainable Development Commission 2007 [34]

Table 8.4 shows the SDC's estimates. Unfortunately it doesn't include the Dee, Morecambe Bay, the Solway or any of the ones on the east coast, and so is missing some of the bigger ones.

Table 8.4: 'Top UK sites for tidal power' (from SDC 2007 [34])

Site name	Resource (TWh/year)
Severn	17
Mersey	1.4
Duddon	0.212
Wyre	0.131
Conwy	0.06

8.7 Burrows et al, 2009

This study has been published in at least three different versions. The first and definitive one is a report for the North West Regional Development Agency, who funded the work [35]. Shortly afterwards the results were published as a paper in the journal Applied Ocean Research [36] and in 2013 it appeared in a special edition of Phil. Trans. Roy. Soc. A. on marine renewables [37].

These researchers carried both 0-D and 2-D modelling of five barrages—Severn, Solway, Morecambe Bay, Mersey and Dee. Table 8.5 shows the results of the 0-D modelling and compares them to the results of previous studies. Table 8.6 shows the results of the 2-D modelling.

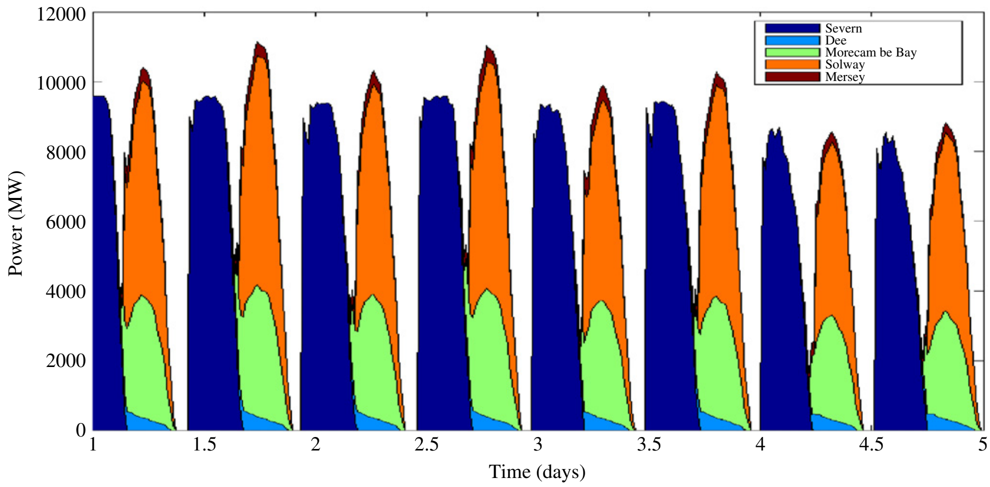
Table 8.5: '0-D modelling outcomes.' (Table 1 of Burrows et al 2009 [36])

Ebb-mode calculations	Mean tidal amplitude, h (m)	Basin area, S (km2)	Prandle's annual energy (TWh)	DoEn (1989) annual energy (TWh)	Joule project annual energy (TWh)
Solway Firth	2.74	∼820	13.1	10.05	8.44
Morecambe Bay	3.07	∼330	6.62	5.40 (6.96a)	5.83
Mersey	3.23	∼62	1.38	1.32	1.07
Dee	2.98	∼58	1.1	1.25	1.04
Severn	3.5	∼450	11.73	12.9	11.12
Total			33.93	30.92	27.5

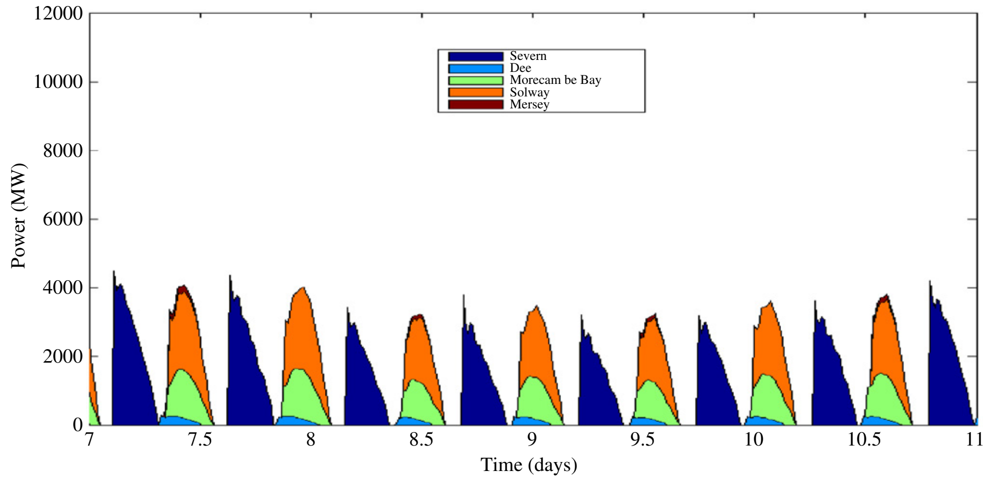
Table 8.6: Outcome from conjunctive (2-D) modelling. (Table 5 of Burrows et al 2009 [36])

Barrage	Number of turbines	Total capacity (MW)	Sluice gate area (m2)	Annual energy (TWh)	Annual energy available in tide (TWh)	% of available energy extracted (%)
Solway Firth	180	7200	28800	9.66	47.94	20
Morecambe Bay	80	4000	14400	5.98	24.88	24
Mersey	27	648	3888	0.57	2.54	22
Dee	50	1050	3960	0.89	2.35	38
Severn	216	8640	24048	15.81	50.05	32
Total		21538		32.91	127.76	26

An interesting finding of this study is that the time delay between the tide at the Severn and those at the northern estuaries means that power output of the northern barrages occurs in the gaps between the power output peaks of the Severn barrage. Figure 8.2 shows this graphically. There are still times when overall output falls to zero, but these are



(b) Spring series.



(c) Neap series.

Figure 8.2: Power output from the 5 West Coast barrages. (Figure 10 of Burrows et al 2009 [36])

now much shorter than for the Severn barrage by itself and the peak output is smaller than if all the barrages were in phase, making integration into the electricity system easier.

8.8 Crown Estate 2012 [38]

This study

> ...describes *new* findings about the size and distribution of wave and tidal resources around the UK.
>
> Total theoretical UK resources are estimated to be follows:
>
> - Wave: 69 TWh/year (27 GW);
> - Tidal stream: 95 TWh/year (32 GW);
> - Tidal range (barrage schemes): 96 TWh/year (45 GW); and
> - Tidal range (lagoon schemes): 25 TWh/year (14 GW).

Table 8.7: Distribution of tidal energy resources across the UK (Table 2 on page 8 of Crown Estate 2012 [38])

Type	Location	Indicative annual energy [TWh/year]	Indicative maximum power [GW]
Tidal stream	England	34	11
	Wales	28	9.5
	Scotland	32	11
	Northern Ireland	1	0.5
	Total	95	32
Tidal range: barrage schemes	England	57	27
	Wales	23	8
	Scotland	16	10
	Total	96	45
Tidal range: lagoon schemes	England	14	8
	Wales	7	3.5
	Scotland	4	2.5
	Total	25	14

Sources: Black & Veatch (tidal stream) and Energy Technologies Institute (tidal range).

Table 8.7 breaks this down geographically, and also gives estimates for tidal stream schemes.

The value of $96TWh/y$ for tidal barrages is unbelievably high, nearly twice the output given by Baker 1991 [33], shown in Figure 8.1 on page 30, which is pretty exhaustive in terms of the estuaries covered. This large discrepancy is not remarked upon, either in the Summary Report [38] or in the Technical Methodology Report [39] and no explanation is given. A possible interpretation is that it is a typographical error and that they had meant to say $36TWh/y$.

8.9 Summary & conclusion

For tidal range energy it makes sense to consider the five larger west coast barrages. Two sources list all five of these, and Table 8.8 lists them : The overall range is therefore:

Table 8.8: Tidal range summary of studies

	Annual energy production (TWh/y)	
Barrage	Boyle 2006	Burrows et al 2009
Solway Firth	10.05	9.66
Morecambe Bay	5.40	5.98
Mersey	1.32	0.57
Dee	1.25	0.89
Severn	19.7 [a]	15.81
Total	37.72	32.91

[a] Two estimates for the Severn barrage are given: "outer line" at $19.7TWh/y$ and "inner line" at $12.9TWh/y$. Most other studies tend to estimate the Severn at $17TWh/y$

$$32.9 - 37.7TWh/y$$

9 Tidal stream

Most studies of the tidal-stream resource include, in their UK estimates, the large resource present in the Channel Islands. However, the Channel Islands are not part of the UK [6] and, more importantly, are much nearer to France than to England

[6] They are 'Crown Dependencies' meaning that they are independent countries in their own right 'protected' by the UK but not part of it. They don't send MPs to Westminster, they own their own seabed and their energy consumption is not included in DUKES (except for energy imported from the

so if their tidal stream resources were developed they would almost certainly be exported to France. This means that they should be included in France's renewable energy potential, not the UK's. In what follows I have therefore attempted to separate out the Channel Islands' component of the resource estimates.

9.1 ETSU T-05-00155-REP, 1993 [40]

9.1.1 UK including Channel Islands

This study was undertaken by Engineering & Power Development Consultants Ltd, with help from Binnie & Partners (who later became Black & Veatch), Sir Robert McAlpine & Sons Ltd and I T Power Ltd. Its conclusions are:

> The total tidal stream energy resources identified in this study amount to ~~some~~ $\boxed{58TWh/year}$, of which $46.5TWh$ is attributed to sites where machines of over $100kW$ size would be installed and the remainder from sites with smaller sets.

9.1.2 Channel Islands

Tables 6.4 and 6.5 on page 6-7 of the report list the 33 sites included in the estimate. Of these, eight are in the Channel Islands and their combined annual energy production is $\boxed{15.921TWh/year}$

9.2 JOULE II Study, 1996 [41]

This study was done by Technomare SpA and IT Power Ltd. It assessed 106 sites around the European coastline and estimated that these could produce $48TWh/year$ with an installed capacity of around $12,500MWe$.

9.2.1 UK including Channel Islands

It did not break this down by country, although it would be possible to do so using the table of sites provided. Binnie Black & Veatch 2001 (see Section 9.4) must have done this as they say that the the JOULE report gives the UK potential as $\boxed{31TWh/y}$. I have not checked this as it would involve too much effort, but assume that it is consistent with Black and Veatch's other studies and includes the Channel Islands.

9.2.2 Channel Islands

The Summary Table on pages 13 to 16 of the report lists all 106 EU sites and their characteristics, including annual energy production. Sites 44 to 48 are in the Channel Islands and have a total AEP of $\boxed{10.98TWh/y}$

9.3 ETSU 1999

9.3.1 UK including Channel Islands

> The accessible tidal stream resource for the most suitable sites in the UK (including the Channel Islands) is estimated to be approximately $\boxed{36TWh/year}$. The actual resource is higher but the current velocities in the remaining areas are so low that their exploitation would be hopelessly uneconomic.

9.3.2 Channel Islands

The report did not give enough information to separate the Channel Islands from the total.

9.4 ETSU T/06/00209/REP, 2001 [42]

This report was done by Binnie Black & Veatch. It's objective was to assess the commercial prospects of Marine Current Turbines Ltd's Seaflow / Seagen concept, for which it concluded that:

UK, which is included because of a quirk of UK trade statistics whereby exports to the Channel Islands or the Isle of Man are not classed as exports, so the compilers of DUKES can't disentangle them from UK consumption).

> ... it seems likely that, after development, the unit cost of energy from sites in water depths of between $20m$ and $50m$ and with peak velocities during mean spring tides greater than $2m/s$ will lie in the range $4-6p/kWh, \ldots$

The study also reassessed the resource estimates in the 1993 study and concluded that:

(ii) It appears that assumptions made in the 1993 review led to the energy available from a single unit being under-estimated significantly, possibly by a factor of 3. This would have had a major influence on the estimated unit cost of energy and has implications for the size of the resource available around the United Kingdom, suggesting it may be more than the $58TWh/yr$ quoted then. This estimate depends on assumptions about array dimensions, however, which have not been examined in this study. The 1996 EC review estimated the resource to be $31TWh/yr$.

(iii) A significant proportion of the available resource appears to be at sites that are in water depths greater than 50m, are remote from areas where the demand is significant, or both. Development at these sites will require major investment and advances in the technology to be commercially viable. The size of the resource available using current technology and small to medium sized schemes is likely to be about $\boxed{10TWh/yr}$, based on the 1993 review estimates.

As this study restricts itself to the small subset of the resource that can be exploited by the Seaflow / Seagen machine, it can't be included in our total.

9.5 Black & Veatch 2004 [43]

This study looked at 57 UK sites 33 of which were from the ETSU 1993 study and 24 were from the JOULE 1996 study. It used the 'flux method', which differs from the 'farm method' used in previous studies as follows:

The Farm Method – Extraction methodology based on developing an array of tidal stream devices that each extract an equal amount of energy from the incoming flux. The number of devices and hence the extracted energy is purely dependent on the size of the device, its efficiency, and the packing density within the plan area.

The Flux Method – Extraction methodology based on the use of only the incoming kinetic energy flux across the front cross-sectional area of a flow channel. This is independent of the device type, efficiency and packing density, taking only the kinetic energy flowing in the channel into account.

In the flux method the total flow of energy through the site is estimated and a proportion taken as the 'available' resource. This proportion, called the 'significant impact factor' or SIF, is defined as the maximum amount of energy that can be removed from a tidal flow before unacceptable effects are observed, such as changes in coastal processes. The SIF is clearly site specific and would require a great deal of work to establish for each site. In the absence of anything better it is taken as 20% for all sites.

Resource subsets are defined as follows:

Total – Total energy over a year that exists within a flow of water, using the Flux Method.

Available – Calculated by use of the Flux Method, this is the total energy over a year that could be extracted from a flow without causing significant changes to flow momentum, or significant environmental impact to the site or other areas. It is equal to Total Resource multiplied by Significant Impact Factor.

Extractable – Total energy over a year that could be produced in theory using the Farm Method.

Extractable and Available – The smaller of Extractable or Available

9.5.1 UK including Channel Islands

Table 9.1 on the next page shows the results for the 'Extractable and Available' resource

9.5.2 Channel Islands

'Appendix B - BV 2004 Resource Calculation Sheet' lists all the sites used in the estimation. Eight sites in the Channel Islands are included, totalling $4.38TWh/y$.

Strangely it also includes seven sites in the Irish Republic totalling $0.139TWh/y$. These also need to be subtracted from the total.

Table 9.1: BV 2004 UK Extractable and Available Resource Distribution [Table 5.7 of [43]]

Range (m)	Velocity Range (m/s)					Total
	< 2.5	2.5 – 3.5	3.5 – 4.5	4.5 – 5.5	> 5.5	
< 25	26 (0.1%)	559 (2.6%)	138 (0.6%)	0 (0.0%)	0 (0.0%)	723 (3.3%)
25 – 30	16 (0.1%)	380 (1.7%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	396 (1.8%)
30 – 40	173 (0.8%)	1,294 (5.9%)	2,068 (9.5%)	0 (0.0%)	0 (0.0%)	3,534 (16.2%)
> 40	558 (2.6%)	3,852 (17.7%)	2,524 (11.6%)	6,323 (29.0%)	3,901 (17.9%)	17,158 (78.7%)
Total	774 (3.5%)	6,084 (27.9%)	4,729 (21.7%)	6,323 (29.0%)	3,901 (17.9%)	21,812 (100.0%)

9.6 Black & Veatch 2005 [44]

In this study, Black and Veatch:

- reexamined and 'validated' (whatever that means) the input data (site widths, depths, and velocities) used in their 2004 study for the ten most important tidal stream sites, comparing the data used in Phase I with data from the Marine Energy Atlas and Admiralty Chart / Tidal Stream Atlases;
- added some new sites;
- developed, with RGU[7], more detailed SIF estimates for some of the largest sites.

9.6.1 UK including Channel Islands

The 'technically extractable' resource was estimated to be $\boxed{18TWh/y}$. This is 20% less than the estimate given in Black & Veatch 2004. It was calculated using the following steps, starting with the data from Black & Veatch 2004:

1. Two sites in the Pentland Firth, whose energy flux was decided not to be independent of other sites, were removed.
2. Tidal stream velocities at various Pentland Firth and Channel Island sites were reduced.
3. The estimated SIF for some sites in the Channel Islands, Rathlin Island, and Mull of Galloway were re-evaluated on a site-by site basis with assistance from Robert Gordon University.

Column 4 of Table 9.2 on the facing page shows the effect of steps 1 and 2 and column 6 shows the effect of the third step. The UK resource at this intermediate stage of the calculation is now $13.8TWh/y$. Next:

4. An additional reduction of $0.7TWh/y$ is applied because the sites that are not in the top-ten should also have their SIFs updated. For these sites, rather than calculate updated SIFs from site characteristics as was done for the top-ten ones, they are instead reduced by a constant proportion equal to the average proportional reduction of the top-ten sites. My attempt to replicate this gives $0.658TWh/y$. This reduces the total to $13.1TWh/y$.
5. They then identify some additional sites. This is done in two steps:
   (a) Three new sites at Islay, Carmel Head, and the Isle of Wight, are included. Their SIFs are calculated on a site-by-site basis. The AEPs of these sites add up to $2.5TWh/y$
   (b) A large number of smaller additional sites are assumed to exist. These are assumed to add up to the same total AEP as the three sites above. The total for new sites is therefore $5TWh/y$. Adding this to $13.1TWh/y$ and rounding to the nearest whole number gives $\boxed{18TWh/y}$.

[7] Robert Gordon University, Aberdeen, the originators of the SIF concept.

Table 9.2: 'Summary of Phase I and Phase II Available Resource for top-ten largest sites (updated SIF) ' (Table 4-6 of Black & Veatch 2005 [44])

Rank	Site Name		Phase II, SIF = 20%, all sites		Phase II, Updated SIF [c]	
		$\frac{Phase\,I}{GWh/y}$ [a]	$\frac{AEP}{GWh/y}$	$\frac{\Delta AEP_{Ph.II-Ph.I}}{GWh/y}$ [b]	$\frac{AEP}{GWh/y}$	$\frac{\Delta AEP_{Ph.II-Ph.I}}{GWh/y}$ [b]
1	Pentland Skerries	3,901	4,526	625	4,526	625
2	Stroma P. Firth	2,774	2,114 (eliminated)	-2,774	2,114 (eliminated)	-2,774
3	Duncansby Head	2,031	1,699	-332	1,699	-332
4	Casquets	1,651	1,045	-606	418	-1,233
5	S. Ronaldsay P. Firth	1,518	1,030	-488	1,030	-488
6	Hoy, Pentland Firth	1,377	714	-663	714	-663
7	Race of Alderney	1,365	608	-757	365	-1,000
8	S. Ronaldsay/ P.Skerries	1,147	964 (eliminated)	-1147	964 (eliminated)	-1,147
9	Rathlin Island	866	1,019	153	408	-458
10	Mull of Galloway	806	638	-168	383	-423
	Total top 10 sites	17,436	11,280	-6156	9,542	-7,894
	Total UK sites	21,812	15,655	-6157	13,814	-7,998
	Channel Islands			-1363		-2,233

[a] 'Phase I' is Black & Veatch 2004 and 'Phase II' is Black & Veatch 2005.
[b] $\Delta AEP_{Ph.II-Ph.I}$ is the difference between the Annual Energy Production reported in 'Phase II' and that reported in 'Phase I'.
[c] The only sites that have updated SIFs are in the top ten. All non-top-ten sites still have $SIF = 20\%$.

9.6.2 Channel Islands

Table 9.2 implies that Black & Veatch's 2005 estimate of the total AEP of the sites in the Channel Islands is $2.233TWh/y$ less than the equivalent figure from their 2004 study, which was $4.38TWh/y$. The result is therefore $4.38 - 2.233 = 2.147TWh/y$. Rounding this to the nearest whole number gives $\boxed{2TWh/y}$. This agrees with the last paragraph on page 21 which says:

> The RGU result for the total Channel Islands resource (assuming a 20% SIF) is 2.0 TWh/y for all the Phase I sites ...

9.7 Seapower SW study, 2004 [45]

This study was done by Metoc for the South West Regional Development Agency (SWRDA), which was later abolished. It looked at tidal stream and wave. Table 9.3 shows its results. It goes on to say:

Table 9.3: Capacity Installed in SW Region or Built in SW for Export (Table 7.2 of Seapower SW 1994 [45])

Installation	Low 2010 MW	Low 2020 MW	High 2010 MW	High 2020 MW
Tidal power installed in SW	32	60	60	122
Wave power installed in SW	48	83	71	285
Total installed in SW	80	143	131	407
Built in SW for export	7	252	244	758
Overall total	87	395	375	1165

> Energy generation in the SW region is forecast to be at least 231 GWh/yr in 2010 and 414 GWh/yr in 2020. Values for the high scenario are around 379 and 1,177 GWh/yr respectively. A capacity factor of 33% has been assumed in these calculations.

122MW of tidal stream capacity at a capacity factor of 33% would produce:

$$
\begin{aligned}
122 \times 10^6 W \times \left(\frac{33}{100}\right) \times 8760\frac{h}{y} &= 122 \times 33 \times 87.6 \times 10^6 Wh/y \\
&= 352677.6 \times 10^6 Wh/y \\
&= 0.35 \times 10^{12} Wh/y \\
&= \boxed{0.35TWh/y}
\end{aligned}
$$

9.8 ECI 2005 [46]

This study modelled the time-variability of the tidal stream resource, but scaled its overall size to the numbers from from Black & Veatch 2004 and 2005.

9.9 ABPMer 2007 [47]

This study was carried out for the npower Juice Fund[8], using data from the recently published DTI Atlas of Offshore Renewables [49] in a GIS together with data on bathymetry and 'exclusion constraints'. It concludes:

> The total predicted annual energy yield for UK waters is estimated as approximately $\boxed{94TWh/y}$. Over two thirds of this is located in intermediate waters between 25 and 40m deep.

but

> ...with present technologies this would require approximately 200,000 devices to be deployed across more than 11,000km^2. These results are therefore presented as a reference to the technically achievable maximum energy yield, should political, economic, and grid connection issues allow all areas of good tidal resource to be developed for energy extraction.

It then discusses the 'Exploitable Tidal Energy Resource (Next 5-10 years)':

> The top 50 cells of tidal resource fall within 10 distinct geographic areas. It is predicted that that the deployment of 569 devices are arranged into 30MW farms, totalling an installed capacity of 1,500MW, has the potential to generate over 4.3TWh/y of energy at these sites. This prediction assumes a 100% uptime of all tidal deployed devices and will therefore be slightly reduced in true operating conditions due to turbine down-time for planned and unplanned maintenance.
>
> It has also been calculated that if the 30MW limit on tidal farm size is removed from the analysis these areas have the potential to produce over 27TWh/y of energy, through the deployment of over 3,000 devices creating a total installed capacity of around 9,500MW. This calculation still assumes a maximum turbine rating of between 1.5-5.0MW. It is acknowledged that the cumulative effects on energy removal by successive 30MW rated arrays in areas confined areas of tidal resource, and also grid connection issues, may provide a potential barrier to the deployment of such large capacities. However, it is also possible that future technology developments, creating higher capacity turbines, may enable the predicted energy yields to being realised

Table 9.4 on the next page lists the ten areas referred to above and

9.9.1 UK including Channel Islands

$$\boxed{27.7TWh/y}$$

9.9.2 Channel Islands

$$\boxed{15.1TWh/y}$$

9.10 Sustainable Development Commission 2007 [34]

Table 9.5 on the facing page lists the numbers presented in this report. However, this is only a subset of the potentially exploitable sites in the UK and so can't be taken as an estimate of the total.

[8]'Juice' was a green tariff offered by RWE npower from 2003 to 1010. Part of the deal was that npower would put £10 per customer per year into a fund that would be used to support wave and tidal-stream energy research. The scheme was administered by Imperial College [48].

Table 9.4: 'Summary of best sites of UK tidal resource' (from [47] Table

Location	Number of Cells	Area (km^2)	No. of Devices Deployed*	Installed Capacity* (MW)	Annual Energy Yield* (GWh/y)	Potential† No. of Devices Deployed	Potential† Capacity (MW)	Potential†* AEY (GWh/Y)
Alderney Race	22	63	204	660	1,937	1,483	5,201	15,145
West Islay	7	21	112	210	584	465	896	2,460
South Pentland Firth	6	16	61	180	555	335	1135	3,444
Anglesey	3	9	47	90	238	170	341	873
Ramsay Island	2	6	35	60	183	119	210	631
North Pentland Firth	2	5	17	60	181	103	377	1,150
SW Islay	2	6	30	60	179	131	261	773
Westray Firth	2	5	13	60	177	123	571	1674
Pentland Skerries	2	5	20	60	162	104	312	843
South Isle of Wight	2	6	30	60	161	125	249	663
Total	50	143	569	1,500	4,356	3,157	9,553	27,656
Total (Excluding Channel Islands					2,420			12,511

* Calculated with a 30MW per farm limit.
† Calculated without a limit on farm size.

Table 9.5: 'Top UK sites for tidal power' (from SDC 2007 [34])

Site name	Area	Resource (TWh/year)
Pentland Skerries	Pentland Firth	3.9
Strøma	Pentland Firth	2.8
Duncansby Head	Pentland Firth	2
Casquets	Alderney	1.7
South Ronaldsay	Pentland Firth	1.5
Hoy	Pentland Firth	1.4
Race of Alderney	Alderney	1.4
South Ronaldsay	Pentland Firth	1.1
Rathlin Island	North Channel	0.9
Mull of Galloway	North Channel	0.8
Total		17.5

9.11 MacKay 2009

Professor MacKay uses the same approach as he did for wind. Power is given by:

$$p = C_p \pi \left(\frac{d}{2}\right)^2 \frac{1}{2} \rho v^3$$

the turbines are in a square array of side $\ell = 5d$ so:

$$power\,per\,unit\,seabed\,area = \frac{C_p \pi (d/2)^2 \frac{1}{2} \rho v^3}{(5d)^2}$$

the diameter cancels out, so

$$power\,per\,unit\,seabed\,area = \frac{C_p \pi (1/2)^2 \frac{1}{2} \rho v^3}{5^2} = \frac{C_p \pi \rho v^3}{8 \times 25}$$

he assumes that $C_p = \frac{1}{2}$ so

$$power\,per\,unit\,seabed\,area = \frac{\pi}{200} \frac{1}{2} \rho v^3$$

he then assumes that the density of water is $\rho = 1000kg/m^3$ so

$$power\,per\,unit\,seabed\,area = 2.5\pi v^3 \tag{1}$$

v is assumed to be given by the formula:

$$v = \left(\frac{1}{2}(a_s + a_n) + \frac{1}{2}(a_s - a_n)\cos\left(\frac{2\pi t}{\tau_2}\right)\right)\cos\left(\frac{2\pi t}{\tau_1}\right) \tag{2}$$

where a_s is the peak spring velocity, a_n is the peak neap velocity, τ_1 is the period of the semi-diurnal tidal cycle (12.4 hours) and τ_2 is the period of the spring-neap cycle (354 hours). The annual average power output per unit area of seabed is given by $2.5\pi\overline{|v^3|}$, where $\overline{|v^3|}$ is the cube of the absolute value of the velocity averaged over 1 year and is given by:

$$\overline{|v^3|} = \frac{1}{T}\int_0^T \left|v^3\right| dt \tag{3}$$

where T is 1 year, expressed in the same units as τ_1 and τ_2.

He identified six regions in UK waters that look promising for the deployment of tidal-stream farms. Table 9.6, which

Table 9.6: Tidal power estimates (derived from Table G8 of MacKay 2009 [15])

Region	U (knots)		Power density [a] (W/m^2)	Power density [b] (W/m^2)	Area (km^2)	Annual average power (MW)	AEP GWh/y
	Neap	Spring					
1	1.7	3.1	7	7.04	400	2,815	24,661
2	1.8	3.2	8	7.89	350	2,760	24,177
3	1.3	2.3	2.9	2.94	1000	2,938	25,741
4	1.7	3.4	9	8.73	400	3,491	30,588
5	1.7	3.1	7	7.04	300	2,111	18,496
6	5	9	170	174	50	8,692	76,143
Total						22,809	199,806

[a] Reported by MacKay
[b] Calculated by me from the numbers in the 2nd and 3rd columns using equations (1), (2) and (3)

is derived from Table G8 on page 317 of MacKay's book, lists the characteristics of these sites and calculates the total AEP, which turns out to be $\boxed{200TWh/y}$. This is extremely large compared with all the other estimates. It is quite likely that the areas of seabed chosen by Professor MacKay are too large, and that the fast currents are much more localised.

To check that this agrees with Professor MacKay's figure of $9kWh/person/day$, first divide by 59.5 million people and then by 365 days per year:

$$\begin{aligned} Energy &= \frac{200TWh/y}{59.5 \times 10^6 people \times 365 days/y} \\ &= \frac{200 \times 10^{12} Wh/y}{59.5 \times 10^6 people \times 365 days/y} \\ &= \frac{200 \times 10^3 kWh/y}{59.5 people \times 365 days/y} \\ &= \frac{200 \times 10^3}{59.5 \times 365} kWh/person/day \\ &= 9.2092 kWh/person/day \end{aligned}$$

which agrees, after rounding to the nearest whole number, with Professor MacKay's figure of $9kWh/person/day$.

9.12 Black & Veatch 2011 [50]

This study recycles, with minor changes, Black and Veatch's previous four studies. The changes are:

- a slightly different list of sites

- a new hydrodynamic methodology developed by Edinburgh University
- different subset definitions

The subset definitions are now as follows:

Total Resource – Total energy that exists within a defined tidal system.

Theoretical Resource – Maximum energy that can be harvested from tidal currents in the region of interest without consideration of technical, economic or environmental constraints.

Technical Resource – The energy that can be harvested from tidal currents using envisaged technology options and restrictions (including project economics) without undue impact on the underlying tidal hydrodynamic environment. The technical resource is hence a proportion of the theoretical resource.

Practical Resource – The energy that can be harvested from tidal currents using envisaged technology options and restrictions (including project economics) without undue impact on the underlying tidal hydrodynamic environment, and allowing for the impact of external constraints excluding grid constraints (e.g. shipping, fishing, MOD etc.). The practical resource is hence a proportion of the technical resource.

In this survey we are interested in the 'technical' resource.

9.12.1 UK, including Channel Islands

Tables 9.7 and 9.8 reproduce the overall results. Ignoring the so-called 'optimistic' and 'pessimistic' values, which are

Table 9.7: B&V 2011 'technical' resource

	Total Technical resource TWh/y	Average CoE with learning p/kWh
Pessimistic (P10)	16.4	42.4
Base (P50)	29	19.7
Optimistic (P90)	38.4	14.8

Table 9.8: B&V 2011 'practical' resource

	Total Practical resource TWh/y	Average CoE with learning p/kWh
Pessimistic (P10)	10.3	45.2
Base (P50)	20.6	21
Optimistic (P90)	30	15.5

not explained and are pretty meaningless anyway, the figure we want is $\boxed{29TWh/y}$.

9.12.2 Channel Islands

'Table 5-6 Constraints analysis: methodology and results', on page 44 of the report lists 31 sites for which 'technical AEP' adds to $29.019TWh/y$ and 'Practical AEP' adds to $20.535TWh/y$. The list includes seven sites in the channel islands for which 'technical AEP' adds to $8.07TWh/y$ and 'Practical AEP' adds to $\boxed{5.714TWh/y}$.

9.13 Crown Estate 2012 [38]

This report is discussed in Section 8.7 on page 33 under the heading of tidal range. It gives a 'theoretical' potential of $\boxed{95TWh/y}$, which is considerably larger than most other estimates. The report does not explain why this is, but does say:

> Site selection criteria applied in this assessment were broader than previous studies in the literature and were set in such a way that gave benefit of doubt to device-resource interactions and device designs for financial viability, as well as a consideration of the present technical potential. Some of the installed capacities for

> the Key Resource Areas would not, given present technology, be economically viable to develop at this time because some of the larger areas have low average depths ($10m$) and low mean power densities ($0.5kW/m^2$). Development in these locations would result in high numbers of very low rated (small) converters. Long term, nevertheless, it is conceivable these areas could be utilised by certain technologies.

This seems to imply that the difference could be at least partially due to the selection of larger areas of seabed for the development sites.

Although not stated in the main report, an aside in Appendix C of the Methodology report suggests that the Channel Islands are excluded because the Crown Estate does not own the seabed.

9.14 Summary & conclusion

Table 9.9 gathers together the results of the studies reviewed in this section. It is immediately apparent that the estimates

Table 9.9: Summary of tidal stream resource studies

Study	Annual Energy Production (TWh/y)		
	UK including Channel Islands	Channel Islands	UK excluding Channel Islands
ETSU T/06/00209/REP, 2001 [a]	not stated	0 [b]	10 [c]
ABPMer 2007	27.7	15.1	12.6
Black & Veatch 2005 [a]	18	2.0	16
Black & Veatch 2004 [a]	22	4.52 [d]	17.5
JOULE II Study, 1996	31	10.98	20.0
Black & Veatch 2011 [a]	29	5.7	23.3
ETSU 1999	36	not stated	not stated
Scotland's renewable resource + Seapower SW	not stated	not stated	$33.5 + 0.35 = 33.85$
ETSU T-05-00155-REP, 1993 [a]	58	15.92	42.1
Crown Estate 2012 [a]	not stated	not stated	95
MacKay 2009	not stated	not stated	200

[a] Carried out by Black & Veatch, its predecessor Binnie, Black & Veatch or its predecessor Binnie & Partners.
[b] Not stated but I assume that the Channel Islands would not be suitable for 'small to medium sized schemes'.
[c] '...resource available using current technology and small to medium sized schemes.' Also says: '...resource available around the United Kingdom, ... may be more than the $58TWh/y$ quoted' in the ETSU 1993 report, but didn't estimate by how much.
[d] Also includes some sites in the Irish Republic.

cover a wider range than any other technology—a factor of 20 between the highest and the lowest. For this reason, I have decided to discard the *two* lowest and *two* highest estimates. The overall range is therefore:

$$\boxed{16-42TWh/y}$$

10 Wave

This section only reports studies that have produced estimates of annual energy production. It does not include studies that just calculate the resource intensity, such as the Mollison trilogy [51, 52, 53], the 1992 QUB study [54] or the DTI Atlas [47].

10.1 Leishman and Scobie 1976 [55]

This says:

> Based on this approach and using wave data obtained from the National Institute of Oceanography and from the National Physical Laboratory, mean annual power levels were calculated for various locations off the UK coast. The level of the power available is very sensitive to location. Off Lands End, for example, the mean

power output was calculated to be around $27kW/m$ whereas in the Atlantic off the Hebrides power levels can reach $70kW/m$.

A simple relationship between 50-year design waves and energy levels was deduced enabling maps of annual energy available to be built up. It was estimated that the wave energy on a 1700-mile contour 10 miles from the shore around Great Britain is around $\boxed{500\,million\,megawatt\,hours}$ (equivalent to a mean power level of $21kW/m$). This is more than twice the combined annual energy output of the Electricity Boards in the UK*.

Should wave power become a serious proposition there may have to be a reconsideration of navigational clearways; if allowance were made for existing recommended clearways it is estimated that the 1700 miles avail- able would be reduced to 500-1000 miles depending on distance from the shore.

10.2 Winter, 1980 [56]

This publication is not available for free, therefore I have not been able to access it. Its abstract is available, however. This says:

> Previous estimates of wave energy around the United Kingdom have been made by extrapolating measurements from a few sites to the whole UK seaboard. Here directional wave spectra are used from a numerical wave model developed by the Meterological Office, to make estimates which are verified where possible by observation. It is concluded that around $30GW$ of power is available for capture by wave energy converters: when estimates of converter spacing and efficiency are considered an average of about $7GW$ of electrical power could be supplied. This resource estimate is smaller than previous ones, though consistent with them when factors such as the directional properties of waves and the likelihood that converters will be sited near coasts are included.

$7GW$ annual average output translates into

$$\begin{aligned} 7GW &= 7 \times 10^9 W \times 8760 \frac{h}{y} \\ &= 7 \times 10^9 W \times 8.76 \times 10^3 \frac{h}{y} \\ &= 7 \times 8.76 \times 10^{12} \frac{Wh}{y} \\ &= \boxed{61.32TWh/y} \end{aligned}$$

10.3 ETSU R26, 1985 [57]

This says:

> When the wave energy programme began, estimates suggested that the potential resource around the UK coast was enormous. It is now evident from wave measurements and calculations which take account of geographical limitations and the overall conversion efficiency of the assessed wave energy stations that technically achievable UK resource does not exceed $6GW$ mean annual power. This is equivalent to approximately $\boxed{50TWh}$ of energy per year or $20Mtce$ per year representing about 6% of the total current primary demand for energy in the UK. This achievable resource will probably be further limited in practice by environmental and economic constraints.

10.4 Lewis 1985 [58]

This study was undertaken for the European Commission. It says on page 1 that:

> The total power available at all coastlines [in the European Community] is estimated to be $92GW$ and if the Iberian peninsula is included [Spain and Portugal joined the EC in January 1986] the total rises to about $110GW$.

and

There has been no coordinated wave measurement programme European waters to assess the potential wave energy resource. Some areas have a large number of wave measurement stations, where others have none (see figure 2.10). The estimated total wave energy resource is $92GW$ which represents about 70% of present E.C. electricity consumption. About $66GW$ is the resource along the Atlantic Coastline, $1.5GW$ on the North Sea coast and about $25GW$ in the Mediterranean. All of this resource will not be capable of utilisation and it should be noted that these values are based on gross estimates of wave climate.

and

2.4.3 The Atlantic Coastline

The sea areas around U.K. have a high density of wave measurement stations (Draper 1978). Detailed measurements have been made at the South Uist site with an annual mean incident wave energy of $48kW/m$. It has been estimated that the total resource is $\boxed{30GW}$ (Winter 1980). There are virtually no wave measurements off the Irish west coast. Mollison (1982) used wave data from the U.K. Met. Office model and showed wave energy varied from $24kW/m$ to $70kW/m$ and recent data analysis (Lewis 1984) for a station close to the shore gives a value of $55kW/m$. These figures suggest that the Irish resource will be $25GW$. C.N.E.X.O. have been responsible for a systematic series of measurements in the Gulf of Gascoigne. Wave data was recorded at three stations for a year with a number of gaps. The average wave energy was $16kW/m$ (Ollitraut 1982) with the highest values recorded in the South. The French resource in this area is estimated as $11GW$. The total resource therefore $66GW$.

For the UK, $30GW$ annual average output would be equivalent to:

$$\begin{aligned} 30 \times 10^9 W \times 8760 h/y &= 30 \times 10^9 W \times 8.76 \times 10^3 h/y \\ &= 30 \times 8.76 \times 10^9 \times 10^3 Wh/y \\ &= 30 \times 8.76 \times 10^{12} Wh/y \\ &= 30 \times 8.76 \times TWh/y \\ &= \boxed{262.8 TWh/y} \end{aligned}$$

10.5 Thorpe 1992 (ETSU R72) [59]

The technical UK offshore wave energy resource is large ($7-10GW$ annual average) but the practicable resource will be much smaller because of operational and economic constraints.

$7-10GW$ annual average would be equivalent to $\boxed{61.32TWh/y}$ to $\boxed{87.6TWh/y}$.

10.6 ETSU 1994

Table 10.1 reproduces the figures quited in ESU 1994.

Table 10.1: Accessible wave energy resource for the UK at $\leqslant 10p/kWh$ (from ETSU 1994 [4]).

Discount rate (%)	Location	England & Wales (TWh/y)	Scotland (TWh/y)	Northern Ireland (TWh/y)	UK (TWh/y)
8	Shoreline	0.01	0.39	0	0.4
8	Offshore	0	≈ 0.03	0	≈ 0.03
15	Shoreline	0.01	0.29	0	0.3
15	Offshore	o	0	0	0

10.7 DTI 1994

Table 10.2 on the next page reproduces the figures presented in Energy Paper 62.

Table 10.2: UK Wave Energy Resource (Table 2, page B15 of DTI 1994 [5])

	Accessible Resource (TWh/year) at less than 10p/kWh (1992). 8% discount rate.	Maximum Practicable Resource (TWh/year) in 2005 at less than 10p/kWh (1992). 8% discount rate.
Shoreline	0.4	0.25
Offshore	0.03	0.03

The accessible resource is therefore $\boxed{0.43 TWh/y}$.

10.8 ETSU 1999

Table 10.3 reproduces the figures presented in ETSU 1999 [6].

Table 10.3: The UK Wave Energy Resource (Tables 2 and 3 of section on Wave Power from ETSU 1999 [6]).

Location	Annual Energy Production (TWh)	
	Accessible	Practicable
Shoreline	$\approx 2^*$	0.4
Nearshore	$100-140$	2.1
Offshore	$600-700$	50
Total	$702-842$	52.5

* This is only for the most favourable sites.

The accessible resource is $702-842 TWh/y$.

10.9 Thorpe 1999 [60]

Resource adjectives:

Natural resource: the total yearly amount of wave energy in the seas around the UK.

Accessible resource: used but not defined, probably synonymous with 'natural'.

Technical resource: the amount of energy that could be produced.

This says that the technical resource is $52.5 TWh/y$ as broken down in Table 10.4

Table 10.4: The UK Wave Energy Resource (from Thorpe 1999 [60] Tables 9.3 and 9.4)

Location	Annual Energy Production (TWh/y)	
	Accessible	Technical
Shoreline	$\approx 2^*$	0.4
Nearshore	$100-140^*$	$2.1^\dagger$
Offshore	$600-700$	50
Total	$702-842$	52.5

* This is only for the most favourable sites.
† includes contribution from wind turbine in OSPREY devices.

10.10 Scotland's Renewable Resource, 2001 [8, 9, 10]

This reported $\boxed{45.7 TWh/y}$ for wave (see Table 3.1 on page 5)

10.11 Seapower SW study, 2004 [45]

This study estimated that 285MW of wave power capacity could be installed in the South West by 2020 and could operate at a capacity factor of 33%. This would produce:

$$\begin{aligned} 285 \times 10^6 W \times \left(\frac{33}{100}\right) \times 8760\frac{h}{y} &= 285 \times 33 \times 87.6 \times 10^6 Wh/y \\ &= 823878 \times 10^6 Wh/y \\ &= 0.82 \times 10^{12} Wh/y \\ &= \boxed{0.82 TWh/y} \end{aligned}$$

10.12 MacKay 2009

Professor MacKay assumes $40kW/m$, $1000km$ of Atlantic coastline and a transformation efficiency of 25%. This gives:

$$\begin{aligned} 40kW/m \times 1000 \times 10^3 m \times 25\% \times 8760h/y &= 40 \times 10^3 W \times 1000 \times 10^3 \times \frac{25}{100} \times 8760h/y \\ &= 40 \times 10^3 \times 10^3 \times 10^3 \times 0.25 \times 8.760 \times 10^3 Wh/y \\ &= 40 \times 0.25 \times 8.76 \times 10^{12} Wh/y \\ &= \boxed{87.6 TWh/y} \end{aligned}$$

10.13 Amec 2012 [61]

Resource-adjectives:

Total Resource (TWh/y): The total resource arriving in UK waters. It is the total resource flowing over a single frontage (or group of frontages) that are arranged to give the highest overall energy availability to the UK. These frontages do not take into account potential location constraints such as water depth and distance to shore.

Theoretical Resource (TWh/y): The maximum energy available from a set of frontages positioned in realistic locations based on areas likely to have the most competitive low cost of energy.

Technical Resource (TWh/y): The energy available from the theoretical frontages using envisaged technology options.

Practical Resource (TWh/y): The proportion of the technical resource that can be extracted taking into account locations constraints such as sea uses and environmental impacts.

I think that 'technical' is the one we want, as this refers to output of the devices, whereas 'total' and 'theoretical' are the energy input to the devices, though this isn't clearly stated in the report. The study envisages 1000km of wave device arrays located an average 180 km from shore.

Table 10.5 shows the results. So the figure we want is $95 + 10 = \boxed{105 TWh/y}$

Table 10.5: Summary of resource estimates for offshore and nearshore wave energy farms (Table 5.1, page 37 of Amec 2012 [61])

	Offshore		Nesarshore	
	Annual energy [TWh/y]	Mean power [GW]	Annual energy [TWh/y]	Mean power [GW]
Total	230	26	230	26
Theoretical	146	18	133	15
Technical	95	11	10	1
Practical	70	8	5.7	0.6

10.14 Crown Estate 2012 [38]

This study presents results on tidal range, tidal stream and wave. It is first discussed in Section 8.8 on page 32, in the Section 9 on tidal range. For wave, the answer is $\boxed{69 TWh/y}$, broken down geographically as shown in Table 10.6.

Table 10.6: Distribution of wave energy resources across the UK (Figure 1, page 8 of Crown Estate 2012 [38])

Location	Indicative annual energy [TWh/year]	Indicative maximum power [GW]
England and Wales	23	8.7
Scotland	46	18
Total	69	27

10.15 Summary & conclusion

Table 10.7 summarises the results of the studies described above.

Table 10.7: Wave summary of studies

Study	Accessible resource (TWh/y)
ETSU 1994 and DTI 1994	0.43 [a]
ETSU R26, 1985	50 [c]
Scotland's Renewable Resource + Seapower SW	$45.7 + 0.82 = 46.52$
Winter, 1980	61.32
Crown Estate, 2012	69
Thorpe, 1992	61.32 to 87.6 [d]
MacKay, 2009	87.6
Amec, 2012	105 [b]
Lewis, 1985	262.8
Leishman and Scobie, 1976	500
ETSU 1999 & Thorpe 1999	702 to 842

[a] Available at $\leqslant 10p/kWh$ at a discount rate of 8%
[b] Called 'technical' in Amec 2012
[c] Called 'technically achievable' in ETSU R26, 1985
[d] Called 'technical' in Thorpe 1999

These estimates seem to cluster in the range $50 - 105TWh/y$ so rounding to 1 sig-fig gives:

$$\boxed{50 - 100TWh/y}$$

11 Bioenergy

Bioenergy is very diverse. For the purposes of this exercise, it can be divided into two main categories:

1. Energy derived from plants that are grown for the specific purpose of providing energy and have no other use (energy crops).

2. Energy derived from plant or animal material that is, or is present in, wastes of various sorts.

The former have the disadvantage that they require land that could otherwise be used for growing food. The latter have the problem that the energy content of the largest waste streams is likely to decline over coming years as the waste hierarchy becomes more rigorously applied.

11.1 ETSU 1994

Table 11.1: Bioenergy resources from [4]

	Resource TWh/y
MSW incineration	31.5
Landfill gas	5.3
Specialised industrial wastes	4.7
Agricultural & forestry wastes	
Forestry Wastes	2.8
Straw	7.29
Wet Agricultural Wastes	2.86
Energy crops	194
Total bioenergy	248.45

[a] Estimated

11.2 Energy paper 62

Table 11.2: Municipal and industrial waste resource from [5]

	Accessible Resource (TWh/year) at less than 10p/kWh (1992). 8% discount rate.	Maximum Practicable Resource (TWh/year) in 2005 at less than 10p/kWh (1992). 8% discount rate.
MSW + general industrial wastes	31.5	4.2 to 5.7
Sewage sludge		0.4
Specialised industrial wastes	4.7	3.0 to 4.2

Table 11.3: Landfill gas resource from [5]

Accessible Resource (TWh/year) at less than 10p/kWh (1992). 8% discount rate.	Maximum Practicable Resource (TWh/year) in 2005 at less than 10p/kWh (1992). 8% discount rate.
5.3	6.4 to 7.7

Table 11.4: Agricultural & forestry waste resource from [5]

	Accessible Resource (TWh/year) at less than 10p/kWh (1992). 8% discount rate.	Maximum Practicable Resource (TWh/year) in 2005 at less than 10p/kWh (1992). 8% discount rate.
Straw	10.2	2.2
Forestry	5.0	1.4
Animal slurries	2.9	1.4
Green farm wastes	1.0	0.3

Table 11.5: Energy crops resource from [5]

Accessible Resource (TWh/year) at less than 10p/kWh (1992). 8% discount rate.	Maximum Practicable Resource (TWh/year) in 2005 at less than 10p/kWh (1992). 8% discount rate.
194	89

11.3 ETSU 1999 [6]

Table 11.6: Bioenergy resources from [6]

	Calorifc value	Resource		
	MJ/kg (moisture content)	$tonnes\,of\,product$	MW_e	TWh/y
Agricultural & forestry wastes				19.5[a]
Forestry Wastes	19(dry), 13(35%), 10(55%)	1,727,690		
Straw	18 (dry), 15 (15%)	5,727,000		
Poultry litter	15(20%), 9(50%)	1,300,000 [b]	135	
Wet Agricultural Wastes	$25MJ/m^3$ (AD biogas)			2.86[c]
Energy crops	not stated	not stated		33[a]
Landfill gas	not stated	not stated		8[a, d]
MSW incineration	9	27 million		13.5
Total bioenergy				74

[a] Estimated from illustrated cost-resource curve.
[b] '...on an air dry basis of 13.5GJ/tonne'
[c] 'total accessible'
[d] '... about 2.5M tonnes of coal equivalent per year in England and Wales, which equates to approximately 5TWh/year of electricity. ... The potentials for Scotland and Northern Ireland have been estimated using waste arisings data, assuming the gas generation potential per tonne of waste to be the same as in England and Wales. (but weren't explictly stated)

11.4 MacKay 2009

11.4.1 Energy crops

Professor MacKay says:

> ...the best performance of any energy crops in Europe is closer to $0.5W/m^2$.

He must therefore be referring to heat rather than electricity. He then says:

> Let's cover 75% of the country with quality green stuff. This is the same as the British land area currently devoted to agriculture.

Then using Professor MacKay's value for the area of the UK, $244,000km^2 = 244 \times 10^3 \left(10^3 m\right)^2 = 244 \times 10^9 m^2$, we get

$$\begin{aligned} 0.5W/m^2 \times 244 \times 10^9 m^2 \times 75\% \times 8760h/y &= 0.5W \times 244 \times 10^9 \times (75/100) \times 8.760 \times 10^3 h/y \\ &= 0.5 \times 244 \times 0.75 \times 8.76 \times 10^{12} Wh/y \\ &= 801.54TWh/y \end{aligned}$$

dividing this by the population (59.5×10^6) and the number of days in a year (365) gives

$$\begin{aligned} \frac{801.54 \times 10^9 kWh/y}{59.5 \times 10^6 people \times 365d/y} &= \frac{801.54 \times 10^3 kWh}{59.5 people \times 365d} \\ &= \frac{801.54 \times 10^3}{59.5 \times 365} \frac{kWh}{person.day} \\ &= 36.908 \frac{kWh}{person.day} \end{aligned}$$

which agrees with MacKay's stated value of $36kWh/d\, per\, person$. He then reduces this by 1/3 to account for processing losses, so gets $24kWh/d\, per\, person$. Applying this factor to our $801.54TWh/y$ gives: $\boxed{534.36TWh/y}$.

This looks like a lot, but it is based on the assumption that *all* agricultural land in the country is turned over to energy crops, which would mean that we would no longer be able to produce any food! let's therefore assume that 10% of this could be devoted to energy crops. This would therefore give $\boxed{53TWh/y}$

11.5 Howes et al, 2011 [62]

This report presents a very thorough and detailed evaluation of the biomass resource potentially available in the UK from within-border sources and from imports from overseas.

Table 11.7: UK 'available' bio-energy resources (TWh/y) from Howes et al, 2011 [62]

	Available for bioenergy use (TWh/y):				
	2010	2015	2020	2025	2030
Sawmill co-products	8.33	8.33	8.33	8.33	8.33
Forest residues	5	5	5	5	5
Small round wood	16.11	16.11	16.11	16.11	16.11
Short rotation forestry	0	0	0	0	4.2
Arboricultural residues	12.22	12.22	12.78	13.33	13.89
Straw and dry agricultural residues	31.39	31.39	31.39	31.39	31.39
Energy crops - scenario 1	0.53	2.33	8.23	19.92	21.09
Energy crops - scenario 2	0.53	2.33	8.23	23.69	64.13
Biodiesel - OSR scenario 1	1.94	2.78	3.33	3.89	4.44
Biodiesel - OSR scenario 2	0.33	0.33	0.33	0.33	0.33
UK bioethanol crops (wheat and sugar beet) Scenario 1	11.67	13.33	15	16.67	18.06
UK bioethanol crops (wheat and sugar beet) Scenario 2	7.78	7.78	7.78	7.78	7.78
Tallow	2.78	2.78	2.78	2.78	2.78
Used cooking oil, UK only	2.53	2.53	2.53	2.53	2.53
Waste wood	22.78	22.5	22.22	21.94	21.67
Renewable fraction of solid waste (dry MSW & CIW)	8.06	17.5	20.28	19.44	19.44
Landfill gas fraction of solid waste	46.11	41.67	34.17	25.83	19.17
AD wet manures	6.39	6.39	6.39	6.67	6.67
AD sewage sludge	3.61	3.61	3.89	3.89	4.17
AD food and green waste	17.5	17.5	17.5	17.5	17.5
Total scenario 1	196.95	205.97	209.93	215.23	216.43
Total scenario 2	191.45	197.97	199.71	206.55	245.08

The average of the ten numbers in the bottom two rows of Table 11.7 is $208.527TWh/y$. Rounding this to the nearest two significant figures gives: $\boxed{210TWh/y}$

11.6 Summary & conclusion

Table 11.8 gathers together the results of the studies reviewed in this section. Discarding the highest and lowest estimates

Table 11.8: Summary of bioenergy resource studies

Stdy	Estimate (TWh/y)
DTI 1994	36.2
MacKay 2009	53
ETSU 1999	74
Howes et al 2011	210
ETSU 1994	248.45

gives a range of:

$$\boxed{53 - 210 TWh/y}$$

12 Overall summary

Table 12.1 gathers together the results of the above sections. Interesting observations include:

Table 12.1: Overall summary resource studies

Technology	Lower estimate (TWh/y)	Upper estimate (TWh/y)
Offshore wind	200	663
Onshore wind	127	470
Solar	84	140
Bioenergy	53	210
Wave	50	100
Tidal range	33	38
Tidal stream	16	42
Hydro	7.5	7.5
Total	570.5	1670.5

1. Onshore wind is the 2nd largest resource and is nearly as big as offshore wind. This means that we cannot really do without it if we want to decarbonise our energy system.

2. The upper end of the range is roughly a factor of three bigger than the lower end.

3. The lower end of the range is bigger than current UK electricity consumption, but quite a lot smaller than total energy consumption.

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Appendices

A Conversion factors

Professor MacKay rightly calls the toe an annoying unit. Unfortunately, DUKES continues to use it. Its value is as follows:

$$\begin{aligned} 1toe &= 10kcal \\ &= 396.83therms \\ &= 41.868GJ \\ &= 11,630kWh \\ &= 11.63MWh \end{aligned}$$

so

$$1ktoe = 11.63GWh$$

The Joule is a Watt-second so the Watt-hour and the Joule are related by the number of seconds in an hour:

$$1kWh = 3.6MJ$$

$$1MJ = \frac{1}{3.6}kWh$$
$$1MWh = 3.6GJ$$

$$1GJ = \frac{1}{3.6}MWh$$

$$1TJ = \frac{1}{3.6}GWh$$

$$1PJ = \frac{1}{3.6}TWh$$

$$1GJ/te = 1MJ/kg = 1kJ/g$$

B Bioenergy data

This appendix contains data that are useful in interpreting bioenergy facts and figures.

B.1 Moisture content

Moisture content is usually quoted on a wet basis (i.e. the mass of water in a sample divided by the mass of the sample *before* drying) but sometimes on dry basis (the mass of water in a sample divided by the mass of the sample *after* drying). Both are equally valid so it is important to be clear which has been used. The relationship between the two is given by:

$$(1 - \phi_w)(1 + \phi_d) = 1$$

where ϕ_d is the moisture content on a dry basis and ϕ_w is the moisture content on a wet basis.

The *mass* of material can be expressed as:

- 'dry tonnes', i.e. what its mass would be if it were all thoroughly dried, sometimes called *oven dry tonnes* or *oven dried tonnes*, abbreviated to odt.
- 'as received' i.e. including the mass of whatever amount of moisture it happens to contain or even
- corrected to a particular moisture content.

B.2 Calorific values of renewable fuels

Every year DECC includes a table of calorific values in DUKES. In theory these are updated every year to reflect changes in the composition of fuels actually used, but ... The most recent set of numbers are shown in Table B.1 on the facing page.

B.3 Dependence of CV on moisture content

Gross CV per dry tonne is independent of moisture content because heat used to evaporate the moisture is regained when the vapour is condensed, and so the GCV of the moist material per dry tonne is equal to the GCV of dry material.

Gross CV per moist tonne is equal to the gross CV per dry tonne multiplied by $(1 - \phi_w)$, which simply corrects for the extra mass:

$$GCV^* = (1 - \phi_w)GCV,$$

where the asterisk, $*$, denotes 'per moist tonne' and the absence of an asterisk denotes 'per dry tonne'. It is possible to think of three permutations of net CV:

1. the net CV of dry material (NCV);
2. the net CV of moist material on a dry basis, (NCV');
3. the net CV of moist material on a wet basis, (NCV^*).

These are related to moisture content according to the following formulae:

$$NCV' = NCV - \phi_d L$$

$$NCV^* = (1 - \phi_w)NCV - \phi_w L$$

where L is the latent heat of evaporation of water, expressed in the same units as the CV.

Quoted values of NCV don't always take such subtleties into account. It is best to use GCV wherever possible because it is less ambiguous.

Table B.1: Calorific values of renewable fuels in the UK in 2013, from DUKES 2014 [63]

	Calorific value (MJ/kg)		
	Net	Gross	Moisture*
Domestic wood (3)	13.3	14.9	20%
Industrial wood (4)	17.3	18.6	0%
Straw	13.4	15.8	15%
Poultry litter (5)	7.6	9.1	16%
Meat and bone	16.8	20	16%
General industrial waste	15.2	16	5%
Hospital waste	13.3	14	5%
Municipal solid waste (6)	6.6	9.5	30%
Refuse derived fuel (6)	13	18.5	30%
Short rotation coppice (7)	11.4	13	16%
Tyres	30.4	32	5%
Wood pellets	15.3	16.7	10%
Biodiesel	37.2	38.7	4%
Bioethanol	26.8	29.7	10%

* DUKES does not say whether the moisure content is expressed on a "dry basis" or a "wet basis".

(3) On an "as received" basis; seasoned logs at 20% moisture content. On a "dry" basis 18.6 GJ per tonne.

(4) Data reported on an oven dry basis of 18.6 GJ per tonne.

(5) The calorific value of poultry litter typically ranges on a net basis from 5 GJ/tonne to 10 GJ/tonne depending upon the moisture content of the fuel. For poultry manure, much lower calorific values should be used.

(6) Average figure based on survey returns.

(7) On an "as received" basis; at 30% moisture content. On a "dry" basis 18.6 GJ per tonne.

B.4 Efficiency of combustion plant

The size of the biomass resource strongly depends on the efficiency of the plant used to burn it. Numerical values are hard to find in the published literature. The following tables are from the only two I've been able to find.

B.4.1 European Commission 2006 [64]

The IPPC BAT reference document for large combustion plant [64], contains a table of thermal efficiency values that the LCP working group considered BAT. This table is reproduced in Table B.2.

Table B.2: Thermal efficiency levels associated with the application of BAT measures for peat and biomass fired combustion plants

Fuel	Combined technique	Unit thermal efficiency (net) (%)	
		Electric efficiency	Fuel utilisation (CHP)
Biomass	Grate-firing	Around 20	75 − 90 Depending on the specific plant application and the heat and electricity demand
	Spreader-stoker	> 23	
	FBC (CFBC)	> 28 − 30	
Peat	FBC (BFBC and CFBC)	> 28 − 30	

FBC: fluidised bed combustion
BFBC: bubbling fluidised bed combustion
CFBC: circulating fluidised bed combustion

B.4.2 European Commission 1998 [65]

Table B.3: Efficiencies of various biomass combustion plants [Table 4.5 of [65]]

Plant (country, start-up year)	Boiler system	Fuels used	Capacity (MWe)	Efficiency			
				boiler LHV	turbine LHV	e.net* LHV	e.net* HHV
Average Zurn/NEPCO	Travelling grate	Wood	25	-[a]	-[a]	29	24
Delano I (USA, 1991)	Bubbling FB	Agr. waste	27	86	35	29	26
McNeil (USA, 1984)	Travelling grate	Wood	50	83	39	30	25
Måbjergværket CHP (DK, 1993)	Vibrating grate (water-cooled)	Straw, Wood, MSW, Nat. gas	34	89	36	30	-[a]
Händelöverket CHP (S, 1994)	Circulating FB	Wood	46	89	38	32	26
Grenaa CHP (DK, 1992)	Circulating FB	Wood, Straw	27	-[a]	37	-[a]	-[a]
Enköping CHP (S, 1995)	Vibrating grate (water-cooled)	Wood	28	96	37	33	28
EPON co-fire (NL, 1995)	Pulverised coal boiler	Demolition wood	20	-[a]	-[a]	37	34
Whole Tree Energy	Pile/grate boiler	Wood, Coal	100	90	41	38	32
ELSAM co-firing scale-up project (DK, 2005)	Circulating FB	Straw, Wood	250	-[a]	-[a]	44	-[a]

* The term 'net efficiency' is not defined in the report. What at first sight seems like the most likely explanation, that it is the overall efficiency on a net calorific value basis, is contradicted by the inclusion of 'LHV' and 'HHV' versions. The next most likely explanation is that it is the efficiency after parasitic loads within the plant have been netted off, which they should be anyway.

[a] No data were available to determine this value

B.5 Crop yields

B.5.1 BBSRC 2004 memorandum [66]

The Biotechnology & Biological Sciences Research Council submitted a memorandum to the House of Lords Science and Technology Committee, reproduced in the latter's 2004 report on renewable energy. This states that:

> Typically a sustainable crop of 10 dry t/ha/y of woody biomass can be produced in Northern Europe rising to perhaps 15 or maybe $20dry\ t/ha/y$ for energy crops in Southern Europe. Thus an area of $1\,(km)^2$ or $100ha$ will produce $1,000dry\ t/y$ enough for a power output $150kWe$ at low conversion efficiency or $300kWe$ at high conversion efficiency.

$300kW_e$per km^2 equates to $0.3W_e/m^2$ and 150 equates to $0.15W_e/m^2$.

A better way to calculate it would be to take the $1,000dry\ t/y$, multiply by the CV per dry tonne, which DUKES says is always $18.6GJ/te$, then multiply by the wood-to-wire efficiency which, based on the discussion in Section B.4 on the preceding page, is 25%.

First, calculate the annual heat output of this $1km \times 1km$ square:

$$\begin{aligned} AHP &= 1,000dry\ t/y \times 18.6GJ/te \\ &= 1,000 \times 18.6GJ \\ &= 1,000 \times 18.6 \times \frac{1}{3.6}MWh \\ &= 5166.7MWh \\ &= 5.1667GWh \end{aligned}$$

Averaging this out over a year gives

$$\frac{5.1667 \times 10^9 Wh}{8.76 \times 10^3 h} = 0.5898 \times 10^6 W_{thermal}$$

This is for $(1km)^2 = (10^3 m)^2 = 10^6 m^2$ so the average output is $0.5898 W_{thermal}/m^2$. Now apply the thermal efficiency of the power plant,

$$AEP = 5.1667 GWh \times 25$$
$$= 1.2917 GWh$$

Averaging this out over a year gives

$$\frac{1.2917 \times 10^9 Wh}{8.76 \times 10^3 h} = 0.14745 \times 10^6 W$$

which is equal to $0.14745 W/m^2$, which agrees almost exactly with the BBSRC's lower figure quoted above. Their higher figure must therefore be referring to a power plant with a wood-to-wire efficiency of 50%, which would represent an enormous advance over current technology.

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