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How does bioenergy compare with other land-based renewable energy sources globally?

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Abstract

The potential power generation from land-based bioenergy is predicted globally using a computer model. Simultaneous consideration of land use, cost and carbon restrictions enables practical evaluation of net power output. Comparisons are made with wind and solar power, and a sensitivity analysis is used to explore the effects of different policy assumptions. Biomass is shown to offer only moderate power-generating potential, and would satisfy less than half of current demand even if all suitable existing arable land were used to grow bioenergy crops. However, bioenergy can be cheap to generate given current economics, and is able to remove atmospheric carbon in some cases if coupled with carbon capture and storage. Wind turbines are able to provide more power globally, but photovoltaic solar panels are the only source considered with the potential to satisfy existing demand. Since land-based bioenergy is also restricted by the need to grow food for an expanding population, and technological developments are likely to greatly increase the viability of other renewable sources, the role of land-based bioenergy appears relatively limited and short-term.

Keywords: bioenergy, carbon emissions, global demand, land use, *Miscanthus*, production cost, renewable energy, solar power, wind power

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Introduction

Present focus on renewable energy is driven by a combination of aims, which include reducing carbon emissions (Schiermeier *et al.*, 2008), increasing energy security (Eaves & Eaves, 2007) and minimising dependence on finite fossil fuel reserves (Mackay, 2008). Bioenergy is a prominent component of many government and industry strategies to exploit renewable energy due to its ability to contribute towards these objectives (Berndes *et al.*, 2003; Bringezu *et al.*, 2009). However, renewable energy capacity remains some way from meeting total demand, supplying just 16% of global energy consumption in 2009 (REN21, 2011). A major challenge is to increase power generation from renewable sources while accounting for concerns such as cost, carbon emissions and available land.

Recent studies have established the potential for renewable energy sources to satisfy global demand (Delucchi & Jacobson, 2011; IPCC, 2011; Jacobson & Delucchi, 2011). In this article, we provide greater scrutiny of bioenergy by comparing it directly against other land-based renewable sources to investigate its role at regional and global scales. Emphasis is placed on spatial results, which are particularly important to account for land use competition (Ehrlich & Pringle, 2008; Smith *et al.*, 2010) and energy distribution (Mackay, 2008).

Computer simulations are used to map predicted global power generation, production costs and carbon emissions. Results for bioenergy are compared against on-shore wind and solar power to assess the relative importance of bioenergy. Practical potentials are estimated for each source by combining model predictions with existing land use data. The investigation is thus able to provide a broader evaluation of the relative importance of bioenergy than previous global studies (Fischer & Schrattenholzer, 2001; Beringer *et al.*, 2011), and allows the merits of bioenergy to be assessed in terms of different policy aims.

We restrict our consideration of bioenergy to *Miscanthus* × *giganteus*, a non-food crop which can be grown on marginal land (Ercoli *et al.*, 1999; Beringer *et al.*, 2011). Its impact on food prices – perhaps the most serious criticism of the possible consequences of bioenergy (Eggers *et al.*, 2009) – is therefore able to be reduced; however, for simplicity only existing arable land is considered in the current study, as this provides a straightforward assessment of the spatial distribution and scale of potential power generation. *Miscanthus* is widely reported to provide higher yields than other candidate bioenergy crops over a range of conditions, hence offering more efficient use of space, and thereby minimising disruption of other land uses (Heaton *et al.*,

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2004; Tilman *et al.*, 2006). Moreover, high levels of biodiversity have been found in *Miscanthus* field studies relative to other agricultural uses (Semere & Slater, 2007). Residues from existing crops are not considered due to the likely negative impact on soil fertility (Andrews, 2006); traditional sources of biomass, such as firewood, are also neglected due to their restricted scope for development.

This study uses an established crop model (Clifton-Brown *et al.*, 2000; Hastings *et al.*, 2009a) to predict bioenergy yields. Incident radiation in the crop model is used to estimate solar panel power generation, and a simple model of wind power is also presented. The aim of the study is to use available global data to provide a straightforward assessment of the importance of bioenergy relative to other land-based renewables, and the modelling approach is deliberately simple and transparent. For simplicity, we focus on power generation rather than demand, storage and transmission. This approach provides clear predictions on the location and magnitude of available renewable power. While several assumptions are necessary to facilitate the study, they are clearly presented and their effects are also investigated.

Materials and methods

Crop and solar calculations

Miscanthus yields are calculated using the crop growth model Miscanfor (Hastings *et al.*, 2009a), which is a development of the Miscanmod model (Clifton-Brown *et al.*, 2000) based on the energy use efficiency method of Monteith (Monteith, 1977; Ewert, 2004). The model uses meteorological and soil data to predict annual crop yields, and has been shown to provide good agreement with field data for *Miscanthus* in Europe and North America (Clifton-Brown *et al.*, 2000, 2004; Khanna *et al.*, 2008; Dondini *et al.*, 2009; Hastings *et al.*, 2009a,b). Growth is calculated according to the product of intercepted photosynthetically active radiation and the empirical radiation use efficiency (Clifton-Brown *et al.*, 2000). Temperature and water stress are accounted for (Hastings *et al.*, 2009a), assuming no irrigation.

Beringer *et al.* (2011) recently modelled global *Miscanthus* yields using the LPJmL vegetation model, which was validated globally against yield data for different crop types; results were compared against Miscanmod in Europe, showing good agreement. Miscanfor has also been successfully compared in Europe against a highly simplified crop model (Pogson, 2011), which also shows strong agreement at a global scale (correlation coefficient 0.7 for historical average yields). In the absence of reliable global field data for *Miscanthus*, the agreement of Miscanfor with different modelling approaches strongly suggests it is a reliable method. It has the advantage of being simpler than the LPJmL model, but with more accurate representation of key marginal areas than the highly simplified crop model.

Incident radiation is calculated in the Miscanfor model according to latitude and time of year, accounting for cloud cover (Hastings *et al.*, 2009a). From this, usable solar power is obtained simply by multiplying by the conversion efficiency of a solar panel. Solar panels are assumed parallel to the Earth's surface; although this will underestimate light interception relative to an appropriately angled surface, the difference is not deemed important to the investigation. No limits are placed on maximum power output (Nelson *et al.*, 2005), efficiency is assumed constant with temperature, and electrical energy storage is not considered. Consideration of solar panels is restricted to standard photovoltaic (PV) cells due to their broader scope than water heating panels and more general applicability than concentrating solar panels; although all types of solar panel are important, standard PV results give a good representation of the scope for solar power. Conversion efficiency is assumed to be 0.1 (Mackay, 2008), which is a fairly conservative estimate.

Wind turbine calculations

Wind turbines are assumed to have horizontal-axis rotors perpendicular to incident wind. Harnessed power is calculated from monthly average wind speed data recorded at a fixed height. At wind speed u, the momentum of air per unit area perpendicular to the wind direction is equal to ρu, where ρ is air density. The wind power q per unit area is found as a function of wind speed by substituting momentum per unit area for mass in the kinetic energy equation (Mackay, 2008):

$$q(u) = 0.5\rho u^3 \tag{1}$$

The power P generated per unit land area is therefore:

$$P(u) = q(u)Bef \tag{2}$$

where e is the efficiency of conversion from wind to mechanical energy, f is the efficiency of conversion from mechanical to electrical energy and B is the area swept by the turbines per unit land area, given by:

$$B = \frac{\pi d^2}{4st} \tag{3}$$

where d is rotor diameter, s is lateral spacing of turbines and t is longitudinal spacing.

Recorded mean wind speed μ_0 is adjusted for turbine height according to the wind profile power-law method (Irwin, 1979):

$$\mu = \mu_0 \left(\frac{h}{h_0}\right)^z \tag{4}$$

where μ is the mean wind speed at the rotor hub, h_0 is the height of measurement, h is the height of the rotor hub and z is a dimensionless constant obtained empirically.

Assuming wind speed follows a Rayleigh distribution (Feijóo *et al.*, 1999), expected power U generated by the turbines per unit land area is calculated as:

$$U = \int_v^w R_\mu(u)P(u)du + P(w)\int_w^x R_\mu(u)du \tag{5}$$

where R_μ is the Rayleigh distribution with mean μ, v is the cut-in wind speed, w is the rated wind speed and x is the cut-out wind speed. Integrals are evaluated by use of the error function (Abramowitz & Stegun, 1964). Expected energy per unit land area is obtained by multiplying U by the time period.

Wind turbines are assumed identical in all regions as data are insufficient to match turbine specifications to local conditions. Turbines are assumed to have rotor diameter d of 80 m, height h of 60 m, cut-in speed v of 4 m s^{-1}, rated speed w of 16 m s^{-1} and cut-out speed x of 25 m s^{-1}, typical for a large turbine (Vestas, 2011). Standard values are used for turbine spacing s and t as 5d and 10d respectively (Manwell *et al*., 2009). Mechanical efficiency e is assumed constant at 0.35 (Hau, 2006); although this is a fairly large simplification, the approximation only applies between the cut-in speed and rated speed, which is where the assumption is most accurate. Electrical efficiency f is also assumed constant, at 0.85 (Hau, 2006). The empirical exponent z in Eqn (4) is assumed 1/7 (Mackay, 2008). Air density ρ is assumed constant at 1.23 kg m^{-3} (International Organization for Standardization, 1999); variation with temperature is beyond the scope of this study. The effect of surface gradient is not considered explicitly, but is implicit to the wind speed data.

Cost calculations

Production costs per unit energy are estimated for the life-cycle of each energy source, neglecting possible changes in land value, technology, fuel costs and infrastructure, and excluding any subsidies. Consideration of distance to users is not made, although an implicit assumption is made for *Miscanthus* that transport costs become prohibitive if plantations are greater than 50 km from power stations or end use.

Cost per unit energy in terms of present value V is calculated as (Smeets *et al*., 2009; van den Broek *et al*., 2000; Wang *et al*., 2011):

$$V = \frac{\sum_{i=1}^{M} \sum_{y=1}^{N} C_i(y)/[1+d]^y}{\sum_{y=1}^{N} E(y)/[1+d]^y} \quad (6)$$

where M is the total of number of costs, $C_i(y)$ is the cost of item i in year y, N is the number of years over which costs are incurred, d is the annual discount rate and $E(y)$ the gross energy yield in year N. Mean yields are used for each productive year.

Crop costs are split into one-off costs (establishment and removal of rhizomes), annual overheads based on land area (land rent, harvest of above-ground matter and storage) and annual transport costs based on yield; this choice of categories is guided in part by available data. Bauen *et al*. (2010) provide these costs for *Miscanthus* in the UK, excluding transport, while Hoogwijk (2004) provides transport costs, labour costs and land costs for general bioenergy crops across global economic regions. Fertiliser costs are neglected due to the low requirements of the crop (Ercoli *et al*., 1999).

To obtain relevant costs across all regions, the costs from Bauen *et al*. (2010) are adjusted according to the costs presented by Hoogwijk (2004) for each region relative to W Europe, taking the mid-point of reported values. Transport costs are taken directly from Hoogwijk (2004). Establishment, removal, harvest and storage costs are scaled as the transport costs of Hoogwijk (2004), since these processes are assumed to rely heavily on machinery, while land costs are scaled according to the land costs of Hoogwijk (2004). The resulting costs are shown in Table 1, and the assumptions are considered further in the Discussion section.

To calculate the average annual cost per unit energy of *Miscanthus*, the values in Table 1 are substituted into Eqn (6), using the mean annual energy yield for each year in the summation, except the first 3 years, where the yield is 0 (Defra, 2007). The crop lifespan is assumed to be 20 years (Beringer *et al*., 2011). The discount rate is assumed to be 0.06 for all regions (Wang *et al*., 2011).

Photovoltaic solar panel costs are assumed 250\$ m^{-2} (based on a near-term estimate by Smestad, 2008) with a lifespan of 20 years at full efficiency (Mackay, 2008). All references to \$ are for USD. Dismantling costs are neglected due to the scrap value of solar panels. Land rent is assumed one-quarter of crop land rent due to the assumed lower value of non-cultivable land, and the possible application of solar panels to existing structures. No other costs are considered, such as maintenance or energy storage.

Wind turbines (as described above) are assumed to cost 2M\$ per turbine to install and 100k\$ yr^{-1} per turbine for maintenance and insurance (DTI, 2005). Land rent is assumed one-quarter of crop land rent due to the sparse coverage of wind turbines allowing other land use to some extent. Land rental costs for wind turbines, as well as solar panels, are likely to be lower in reality, but are used as a conservative estimate. Turbines are assumed to have a lifespan of 20 years (Vestas, 2009); dismantling costs are neglected due to the scrap value of turbines.

Net power and carbon calculations

Net power and carbon emissions for *Miscanthus* are calculated as described by Hastings *et al.* (2009b), including farming inputs using fossil fuel-powered machinery. The crop is assumed to provide no yield for the first 3 years following establishment, hence mean power output of crop production is rescaled by a factor of 17/20 to account for the full lifespan (or the equivalent factor when considering different lifespans). Only unavoidable energy losses are considered; for *Miscanthus* this includes furnace efficiency (which is taken as a minimum loss for all uses) and biomass losses prior to harvest.

For solar panels, energy inputs and carbon emissions of 2300 MJ m^{-2} and 125 kg C m^{-2}, respectively, are spread over the expected lifespan (Stoppato, 2008). For wind turbines, energy inputs and carbon emissions of 72 TJ per turbine and 530 t C per turbine, respectively, are spread over the expected lifespan, assuming current production methods, including metal extraction and processing (Vestas, 2009).

With the exception of carbon calculations for *Miscanthus* which assume previously cultivated land, carbon emissions from land use change are not considered due to the proposed land uses (see below); however, this could be a significant factor were other land uses considered.

Data inputs

Meteorological inputs used to run the Miscanfor model are CRU TS 3.0 monthly cloud, temperature and precipitation data on a 0.5° grid (Mitchell & Jones, 2005). Rather than using mean meteorological data, which inherently smooth out weather conditions, annual results are calculated explicitly, from which average yields are obtained (Hastings *et al*., 2009a). Future predictions use A2 scenario data from HADCM3 CRU climate projections (Johns *et al*., 2003), as described by Hastings *et al.* (2009b). IGBP soil data for field capacity and wilt point are used on a 5′ grid (Global Soil Data Task Group, 2000), and assumed constant with time. Solar power is calculated in the model according to latitude and time of year, and is only

Table 1 *Miscanthus* production costs. Data derived from Bauen *et al.* (2010) and Hoogwijk (2004)

Region	Establishment $/ha	Removal $/ha	Land $/ha/yr	Harvest $/ha/yr	Storage $/ha/yr	Transport $/GJ
Canada	2050	9	85	117	18	0.33
USA	1930	9	185	110	17	0.31
C America	1800	8	130	103	16	0.29
S America	1800	8	130	103	16	0.29
N Africa	2490	11	30	142	22	0.4
W Africa	2490	11	25	142	22	0.4
E Africa	2490	11	25	142	22	0.4
S Africa	1930	9	85	110	17	0.31
W Europe	2800	13	150	160	25	0.45
E Europe	2360	11	80	135	21	0.38
F USSR	2360	11	35	135	21	0.38
M East	1930	9	40	110	17	0.31
S Asia	1930	9	135	110	17	0.31
E Asia	1990	9	170	114	18	0.32
S-E Asia	1620	7	160	92	14	0.26
Oceania	1620	7	30	92	14	0.26
Japan	2300	11	720	131	21	0.37

affected by cloud input data (Hastings *et al.*, 2009a). Wind power is calculated using CRU CL 2.0 mean wind speed data 1961–1990 on a 10′ grid (New *et al.*, 2002); due to the difficulty in accurately measuring and predicting wind speed, global time-series data and future projections are unfortunately not readily available. SAGE global land use data are used to provide the percentage land cover of arable land in the year 2000 on a 5′ grid (Ramankutty *et al.*, 2008), as well as total land suitable for cultivation, and 1992 urban areas on a 0.5° grid (Ramankutty & Foley, 1998; Ramankutty *et al.*, 2002). Summations of results assume a spherical Earth of radius 6371 km (Shirley & Fairbridge, 1997), with the area of each grid cell calculated according to its angular size and latitude.

Land use

Provided production criteria are satisfied in a given grid cell, 10% of any arable land is considered available for *Miscanthus* (pasture land is avoided to lessen soil carbon emissions due to its high carbon content (Davidson *et al.*, 2002); displacement of livestock is not considered since this would simply shift rather than reduce carbon emissions); 10% of any land deemed unsuitable for cultivation is considered for solar panels; and 10% of any land deemed unsuitable for cultivation (excluding urban areas) is considered for wind turbines. It is worth noting that much of the land covered by wind turbines could still be used for other purposes, hence competition for land between the considered energy sources is minimal due to the imposed land use restrictions. The value of 10% is discussed further below, but is easily adjusted since power output scales linearly with available land (since the land inside an individual grid cell is uniform in the model).

Land deemed suitable for cultivation which is not already used as arable land is avoided in all cases due to the importance of its conservation (Ramankutty *et al.*, 2002). The fractions are chosen as an upper bound on what might be possible, and are used to obtain a generous estimation of the availability of renewable power. In reality, land use would clearly vary with location, depending on many factors. Given existing pressures on land use, the arable land fraction may appear particularly high, but previous studies have considered using up to 25% of arable land (FAO, 2008). It is also worth considering the present acceptance of highly inefficient use of land for meat production (Erb *et al.*, 2009), high levels of overconsumption of food in many countries (James *et al.*, 2001), and that around one-third of food produced for human consumption is currently wasted (Gustavson *et al.*, 2011). This study does not advocate that 10% of land should in fact be used, or suggest that use of this land for bioenergy crops would affect these issues over food availability in poorer regions without political intervention; the purpose is simply to establish an estimate of the technical potential so that available technologies can be compared.

The value of 10% land use is clearly somewhat arbitrary. However, results for different land fractions can be obtained simply by multiplying the new land fraction relative to 10%. Furthermore, cost and carbon results are independent of fractional land area, hence are unaffected by the assumption. The value of 10% is chosen as it gives a reasonable idea of potential power generation, and is simple to change to a different value. The major assumption in results is the land types used for each energy source, as opposed to the fraction of each type; this is harder to adjust, but is also a less arbitrary assumption.

Assessment of sources

Direct comparison is made between power generation from each source, avoiding complications of weighting energy according to its type or storage requirements (Mackay, 2008). Power generation is only permitted in locations where net power is positive and production costs and carbon emissions are below 16\$ GJ^{-1} and 20 kg C GJ^{-1} gross energy, respectively, equivalent to oil at 100\$ per barrel, neglecting subsidies (Sims *et al.*, 2006).

Unlike solar and wind power generation, bioenergy crops store chemical potential energy which is not in a directly usable form. Although this has some advantages, such as its scope to be converted for use by existing fossil fuel-powered machinery, it highlights the difficulty to compare power delivery fairly from different sources (Mackay, 2008). Energy values for *Miscanthus* assume it is burnt in a furnace, giving the maximum usable energy (Hastings *et al.*, 2009b). Further energy losses would clearly be involved in generating electrical power; however, unlike the other sources considered, *Miscanthus* energy (i.e. dry matter) could be stored for some time, and transportation of energy over large distances would require minimal changes to existing infrastructure.

Comparison of cost and carbon emissions is similarly difficult between sources. Again, results are presented simply for power generation without consideration of its type or how it will be used.

Results

Net power, production cost and carbon emissions

Maps from global simulations of net power generation for each source are shown in Fig. 1. Results are presented for the power density of each source without accounting for land use, cost and carbon restrictions (Fig. 1a–c); results are masked to show only positive net power generation. Results are also presented accounting for restrictions (Fig. 1d–f); results are masked according to cost and carbon restrictions, and power density rescaled according to available land to show the effective power density of each grid cell. The map presented for restricted solar power (Fig. 1e) uses double the maximum permitted cost as otherwise all solar power is ruled out; this is considered further below. Units are per ha; for values per m^2, multiply by 10^{-4}. $1\ W\ m^{-2} = 315.576\ GJ\ ha^{-1}\ yr^{-1}$. Greenland is missing from crop and solar maps due to data coverage; this is unimportant due to its poor conditions for power generation from these sources.

From Fig. 1a, it is evident that *Miscanthus* is fairly limited in its spatial distribution, unlike solar and wind which are able to generate power over most of the world (Fig. 1b and c). However, production restrictions have little effect on viable regions for *Miscanthus* (Fig. 1d), in contrast with solar (Fig. 1e) and wind (Fig. 1f) which are both drastically reduced in spatial extent by these restrictions (note the doubling of cost restriction in Fig. 1e as mentioned above). Although wind and solar power have relatively high peak power outputs in Fig. 1e and f, these are often in remote areas (such as arctic and desert areas), hence their value is limited. However, both are also able to generate energy in more populated areas if restrictions are relaxed (Fig. 1b and c). To put power generation per unit area into context, average global demand is around $30\ GJ\ ha^{-1}\ yr^{-1}$ and varies for each country by a factor of up to around 10 above or below this value (Mackay, 2008).

Maps of production cost and carbon emissions are shown in Fig. 2. *Miscanthus* provides generally low costs and carbon emissions where it is able to be grown (Fig. 2a and d). Wind is fairly expensive in many areas (Fig. 2c), but has generally low carbon emissions (Fig. 2f). Solar costs (Fig. 2b) and carbon emissions (Fig. 2e) are generally high and scale very closely with the inverse of power generation (Fig. 1b) due to the high manufacturing cost of panels and the assumption of one-off carbon emissions from manufacture.

Comparison of energy sources

Maps showing which sources provide the highest net power (with and without accounting for restrictions), lowest cost and lowest carbon emissions are shown in Fig. 3. It is evident from Fig. 3a that solar panels are able to provide the most power almost everywhere; hence if cost and carbon emissions are not an issue, solar provides the highest output and best use of space. However, accounting for available land, cost and carbon emissions in Fig. 3b, solar power is not currently viable, and no suitable renewable power source exists across large parts of the world. *Miscanthus* provides higher power output than wind in many areas of Fig. 3b, but not necessarily higher total power across whole regions because wind tends to generate more power where it is productive, as considered below. It should be noted for Fig. 3c that while solar power is cheapest per unit energy in many areas, it is still not currently economically viable, and hence does not appear in Fig. 3b; a similar explanation holds for carbon emissions from wind turbines in Fig. 3d. The cost of energy from *Miscanthus* is generally lowest of all the sources where it can be grown, as are carbon emissions, with the notable exception of large parts of Europe.

Regional totals

Regional net power output, cost, carbon emissions and required land area for each source are shown in Fig. 4, accounting for production restrictions. Values for existing power consumption (2008) are also displayed, taken from DOE/EIA (2011). Land use in Fig. 4a is the area of land suitable for each source according to production criteria, all of which is required to generate the net power in Fig. 4d. Results for double the maximum permitted cost are also presented to show the scope of halving production costs or doubling energy prices.

From Fig. 4d it is clear that raising the maximum permitted cost is necessary to satisfy existing power demand without increasing the already high assumed land use fraction or converting protected land. Without raising cost restrictions, around 30% of existing global demand is met, although much of this comes from wind in relatively inaccessible areas (Fig 1f). The result is around 10 times larger than the current figure for the

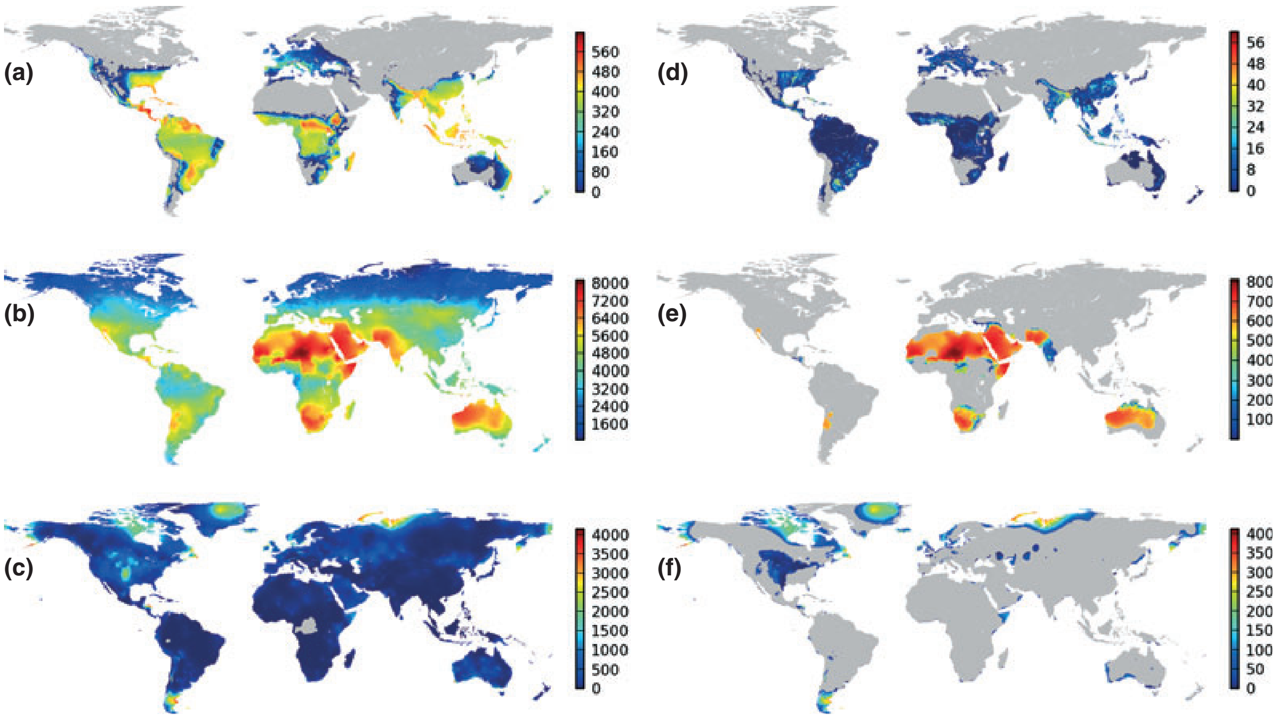

Fig. 1 Global distribution of power generation. Maps of unrestricted mean net power density (climate 1961–1990) for: (a) *Miscanthus*, (b) PV solar panels and (c) wind turbines, all in GJ ha^{-1} yr^{-1}; corresponding maps of mean net effective power density (climate 1961–1990) accounting for land use, cost and carbon restrictions for: (d) *Miscanthus*, (e) PV solar panels (with double cost permitted) and (f) wind turbines, all in GJ ha^{-1} yr^{-1}. Grey areas indicate no power generation.

considered sources (REN21, 2011), and is around double of what is currently provided by all renewable sources, the vast majority being from traditional biomass (such as wood burning) and hydroelectricity (IPCC, 2011; REN21, 2011), which are not considered in this study.

Costs in Fig. 4b are at the lower end of expected values (IPCC, 2011) due to neglecting conversion of biomass into usable energy, energy storage and transmission. Power generation is generally very similar to previous predictions for global totals (IPCC, 2011). Negative carbon emissions from *Miscanthus* in Fig. 4c are due soil carbon gains owing to the exclusive use of previously cultivated land. This assumes carbon capture and storage and a recent conversion of land to *Miscanthus* plantation; negative emissions would decrease in magnitude with time.

Future bioenergy production vs. demand

Net power and land requirements for *Miscanthus* using projected climate data are shown in Fig. 5, assuming the same cost, carbon and land use restrictions as previously defined; projected power demand is also displayed, using data from DOE/EIA (2011). Regional changes in bioenergy production largely cancel out at a global scale, and when compared against projected demand, it appears that bioenergy will only be able to provide a decreasing fraction of future power consumption (Fig. 5b). It is worth noting that changes in power generation are predominantly due to changes in land areas that are suitable for *Miscanthus* to grow, rather than changes in the power output per unit area from the crop; this is evident from the correlation of both graphs in Fig. 5. Possible improvements due to crop breeding are ignored.

Sensitivity to policy assumptions

To examine the effects of different technology and policy assumptions, values for net power, land use, mean cost and mean carbon emissions are presented in Fig. 6 with varying lifespan (i.e. the time period each energy source remains productive before needing replacement), cost and carbon restrictions. Results are presented relative to those obtained from the maximum rescaling of each parameter. Solar panel results are only presented for changing cost restriction because power generation remains zero when varying other parameters. Varying the land fraction has a simple linear effect on power output, and no effect on mean cost and carbon emissions, as discussed in the Materials and methods section (results not shown for simplicity).

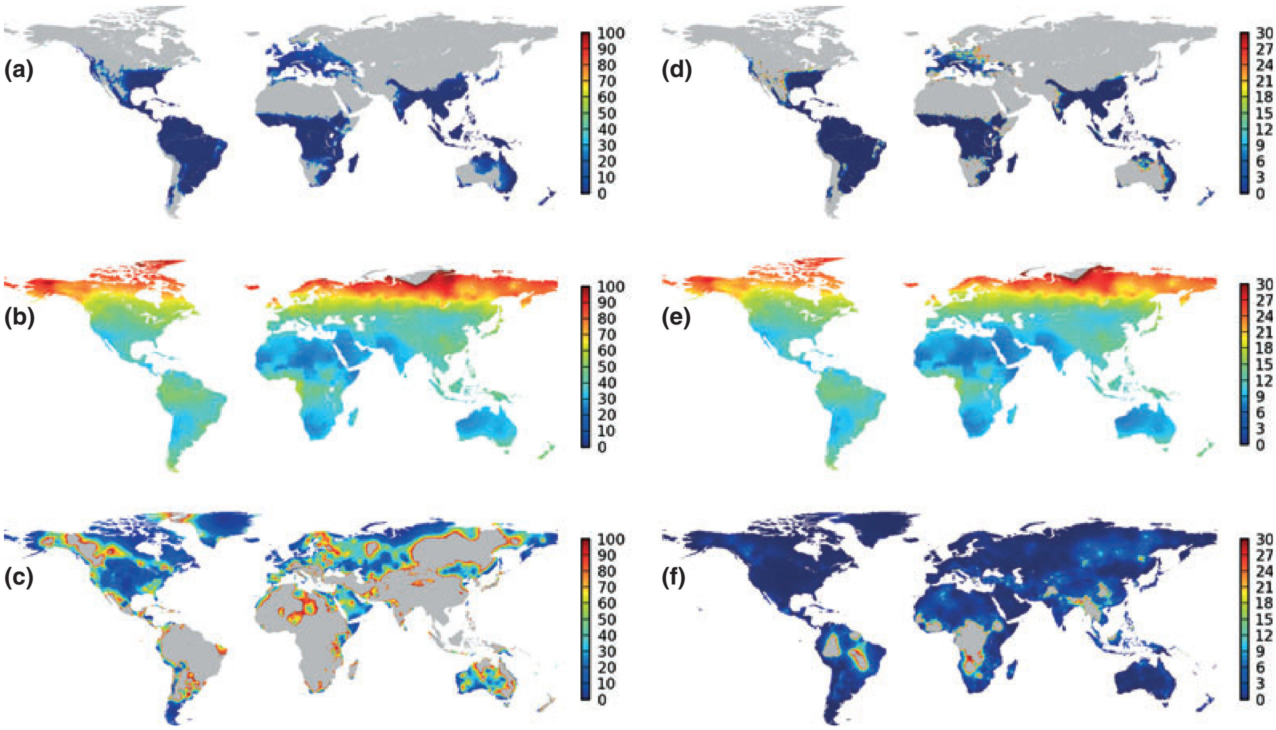

Fig. 2 Global cost and carbon emissions. Maps of mean cost per unit energy up to 100$ MJ^{-1} for: (*a*) *Miscanthus*, (b) PVsolar panels and (c) wind turbines, all in$ MJ^{-1}; maps of mean carbon emissions up to 30 kg C MJ^{-1} for: (d) *Miscanthus*, (e) PV solar panels and (f) wind turbines, all in kg C MJ^{-1}.

Decreasing lifespan lowers average carbon emissions per unit energy from *Miscanthus*, as the combination of restrictions means it can only be grown in increasingly productive areas (due to the fixed energy overhead of unproductive initial years). Increasing lifespan causes a large reduction of wind carbon emissions due to one-off manufacturing emissions (a similar case would hold for solar panels). Cost is brought down for all energy sources by increasing lifespan, but with ever-diminishing returns; power generation and suitable land area similarly increase with lifespan. There are no downsides to increasing lifespan (assuming increased lifespan is not at the expense of other aspects of production, such as manufacturing efficiency and embedded carbon), and it is of most value in reducing carbon emissions from wind turbines.

Increasing permitted carbon emissions has almost no effect on wind power generation, and little effect on bioenergy productivity. The small increase in crop power generation is associated with a large increase in cost, required land area and, particularly, carbon emissions; the extra power evidently comes from marginal areas which generate little power per unit area, and hence are more expensive and less carbon efficient. Increasing permitted carbon emissions therefore appears to have very little benefit.

Increasing permitted cost (equivalent to reducing production cost) has very little effect on bioenergy above current levels, suggesting that production cost is not a limiting factor over present conditions (for biomass production, at least). With wind power, the effect of increasing permitted cost has a fairly even effect on power generation, cost and carbon emissions, hence achievable wind power could be viably increased by lowering production costs. However, solar power displays by far the greatest response to increasing permitted cost; power output increases vastly over a very small range of change in cost, displaying very large returns on relaxing cost restrictions. Within a small percentage change in costs, solar power changes from not being viable to being hugely productive.

Discussion

Bioenergy compared with other renewables

Miscanthus is both unable to satisfy existing demand and generally makes the least efficient use of land (Fig. 4). It is unlikely to increase in productivity either through changes in policy (Fig. 6) or climate (Fig. 5); it is also worth noting that irrigation and fertilisation have previously been shown to be limited in scope to

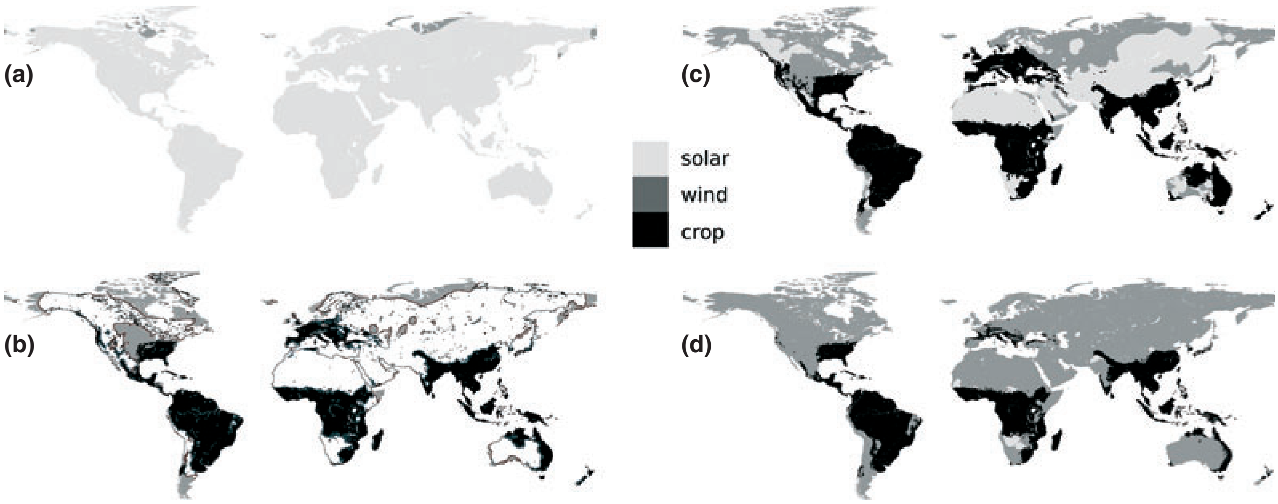

Fig. 3 Global comparison of energy sources. Maps of which source provides: (a) highest power output per unit area, (b) as (a) but accounting for restrictions (without doubling permitted cost for solar panels), (c) lowest cost per unit energy and (d) lowest carbon emissions per unit energy (white areas denote no suitable power source).

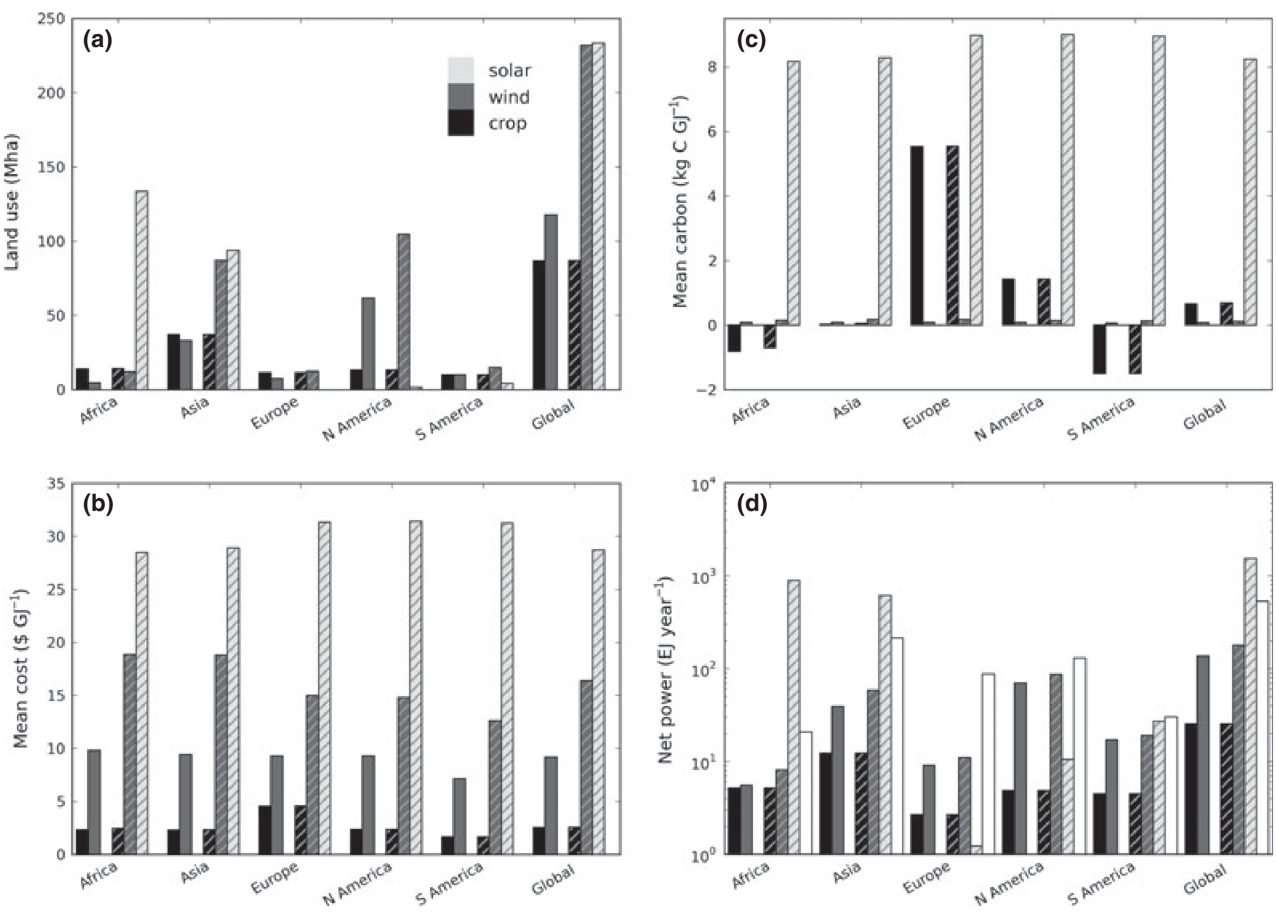

Fig. 4 Regional totals. Graphs of regional totals (climate 1961–1990) – note that the Asian region includes Russia, Oceania and the Middle East – for: (a) land use, (b) cost per unit energy, (c) carbon emissions per unit energy and (d) net power (n.b. log scale) (hatching denotes double maximum cost restriction; white bars in Fig. 4d show power demand from DOE/EIA (2011)).

improve yields (Ercoli *et al.*, 1999; Beringer *et al.*, 2011). Using 10% of suitable arable land to grow *Miscanthus* (which equates to around 6% of all arable land) generates less than 5% of total power demand (Fig 4). Hence, if all suitable arable land were converted to grow *Miscanthus*, it would provide less than half of current demand. However, it can in some cases remove atmospheric carbon in the initial years of establishment (Fig. 4; the effect of this would be permanent if combined with carbon capture and storage technology), is cheap to grow (Fig. 3), and may be of use at a local scale for heat or power generation or a combination of both. Since many of the most productive areas for *Miscanthus* occur in less developed countries, it is possible that bioenergy crop farming could aid sustainable development (Mathews, 2007). However, because areas of high yield also largely coincide with natural forests, it is essential that natural habitats are not converted (as avoided in this study), as this would not only reverse carbon benefits but would also result in many other harmful consequences (Searchinger *et al.*, 2008). Predictions of potential benefits for developing areas must also be balanced by the current situation of biofuels often benefitting developed countries at huge detriment to people in poorer areas (Rice, 2010). Although only *Miscanthus* has been considered in this study, we believe that the use of other bioenergy crops to exploit local conditions would have only a small effect on overall yield relative to total demand (Beringer *et al.*, 2011).

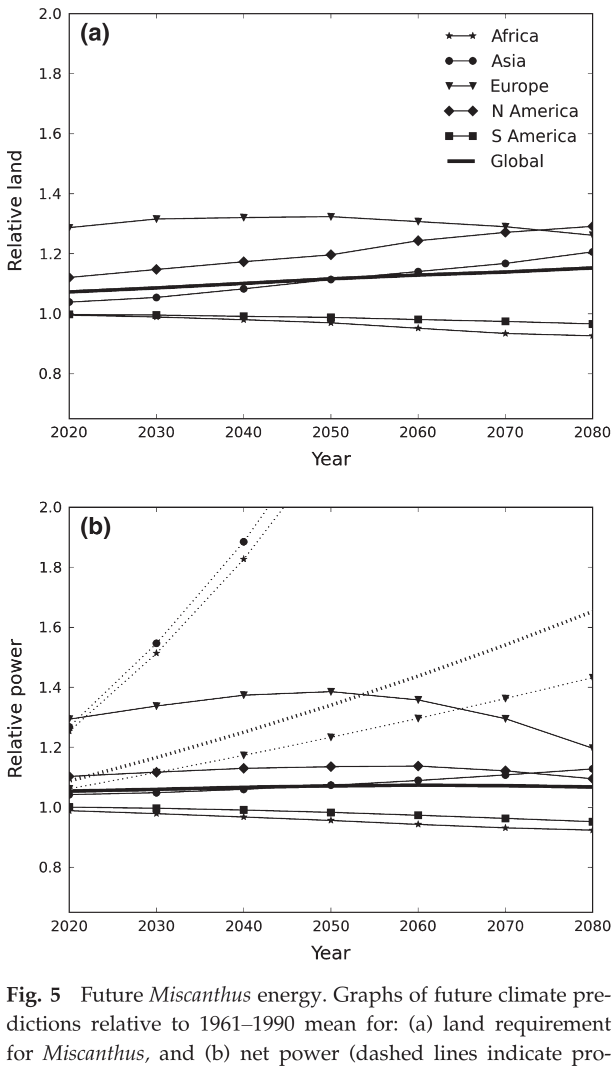

Fig. 5 Future *Miscanthus* energy. Graphs of future climate predictions relative to 1961–1990 mean for: (a) land requirement for *Miscanthus*, and (b) net power (dashed lines indicate projected demand, using data from DOE/EIA (2011); note that Asian and S American projected power demands coincide).

It should be noted that the cost estimates for *Miscanthus* are particularly lenient. Fairly old values have been used, which will tend to underestimate actual costs, especially due to rising fuel prices. Fertilisation costs have also been neglected, although they are likely to be relatively low. Furthermore, results for carbon emissions have assumed the use of carbon capture and storage, which is not only an immature technology but would also significantly increase production costs and reduce available power, neither of which has been accounted for in this study.

Our prediction of total yield from a dedicated bioenergy crop is at the low end of many previous global estimates. Due to our land use restrictions, and consideration of net rather than gross energy, we predict just under 25 EJ yr^{-1} from bioenergy, compared with some previous estimates exceeding 100 EJ yr^{-1} (Beringer *et al.*, 2011; Haberl *et al.*, 2011; Nijsen *et al.*, 2011). Our estimate assumes the use of 10% of suitable arable land, while previous studies have considered partial conversion of natural land and forests. Since Beringer *et al.* (2011) showed good agreement between their crop model and the present one, the large differences in yields are down to land use assumptions rather than modelling disparities. The totals obtained in previous studies may be achievable, but the discrepancies highlight the scale of cultivation required for land-based bioenergy to generate a significant fraction of global demand, as our land use assumptions are already high. Nijsen *et al.* (2011) predicted yields of 32 EJ yr^{-1} from degraded land excluding land currently used for arable, pasture or forest, while Erb *et al.* (2012) estimated yields as low as 26 EJ yr^{-1} without conservation-related constraints, which would lower their prediction further. This raises the question of whether it is sensible to concentrate on using vast areas of land to grow dedicated bioenergy crops; in comparison to other land-based renewable energy sources, which generally require less land per unit energy and have greater power-generating potential, the value of large scale production of bioenergy from dedicated crops is highly debatable. The limited scope for bioenergy presented here is in line with the conclusions of other recent studies (German National Academy of Sciences Leopoldina, 2012).

Wind power is able to provide more power than *Miscanthus* and generally uses land more efficiently. It has higher production costs and carbon emissions per unit energy (Fig. 4), although these are still relatively low. While it is more limited in its spatial distribution than *Miscanthus* with current restrictions on cost and carbon emissions, it has the potential to be productive over far greater areas with these restrictions reduced (Figs 1 and 6). It should be noted that modelling inaccuracy is likely to be the largest for wind power.

Although it appears that solar power is generally not economically viable given current production costs (as described in the Materials and methods section), it has by far the greatest potential of the renewable sources considered in terms of the magnitude, density and distribution of power (Figs 1 and 4), and is also the cheapest power source in many areas (Fig. 3c). With small increases in permitted maximum cost (equivalent to falling production costs), realisable power generation increases rapidly (Fig. 6), and easily satisfies existing demand at double the cost (Fig. 4), using 10% of suitable non-cultivable land. However, the distribution of production would be highly concentrated in few areas at this cost limit (Figs 1e and 4d), and because energy transmission is not accounted for here, it would remain a significant barrier; this is evidently of major importance, along with the issue of energy storage. Solar panels are, however, the only power source considered that has the ability to satisfy current demand, and could deliver energy across the globe if cost restrictions were overcome. The large potential of solar power also means that it could meet projected future demand (Figs 1a and 5b). Unlike dedicated bioenergy crops, which use land that is valuable for many other uses, the proportion of land used for solar panels could realistically be increased in many areas, resulting in up to 10 times the productivity reported here in some regions. Since a large proportion of existing energy demand is for heating, the usefulness of water heating solar panels should be noted, which are significantly cheaper and more efficient than PV panels; the use of concentrating solar panels to maximise power output from strategic locations is also important to consider. The study has been conservative in certain aspects of its estimates of available solar power by assuming non-angled panels and a fairly low conversion efficiency. Although solar power has by far the highest carbon emissions of all the energy sources considered, these are still on average less than half of fossil fuel emissions per unit energy (and electric engines are far more efficient than combustion engines, which would reduce relative demand; Mackay, 2008), hence its high power delivery means it has a large potential to mitigate carbon emis-

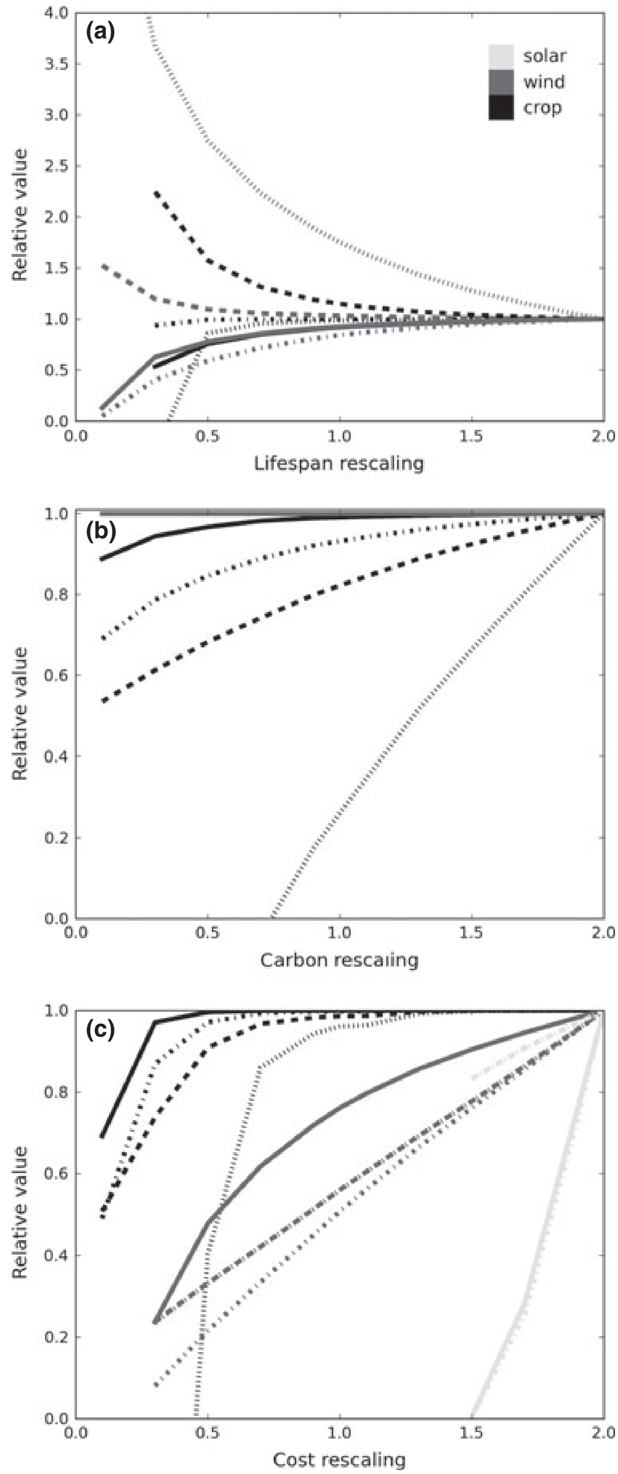

Fig. 6 Effects of changing lifespan, carbon and cost restrictions. Graphs of the normalised effect on each source for power, cost, carbon emissions and land use by changing: (a) lifespan, (b) maximum permitted carbon emissions and (c) maximum permitted cost (solid, total net power; dashed, mean cost; dotted, mean carbon; dash-dotted, total land). Results only plotted where rescaling permits power generation.

sions. However, growth in energy demand may offset much of this (EMF, 2011).

Power supply

Because carbon emissions and production costs are mainly overheads which are independent of generated power for all energy sources, lower prices and lower carbon emissions per unit energy are closely correlated, and hence areas of high yield are trebly valuable for renewable power sources since they minimise land use requirements, costs and carbon emissions. However, benefits of distributing renewable sources more evenly include greater local energy security, shared burden of land use, and cheaper and more straightforward transmission of energy. Fluctuations in power supply are beyond the scope of this study, but it is worth noting that biomass is reasonably suited to providing a store of energy, which could compensate for short-term fluctuations in conditions. Although harvested each year, the difference in seasons between northern and southern hemispheres means that globally there would be two harvests per year.

Future prospects

Given current trends of rapidly increasing population size and energy usage per capita across the world (International Energy Outlook, 2011), and the related need for increased food production (Smith *et al*., 2010), it is unlikely that power demand will decrease or that more land (or even anywhere near as much land) could be used for bioenergy than considered here without converting protected land.

Production costs for many aspects of renewable power are likely to decrease as technologies mature, and it is likely that policies which target the effects of carbon emissions will also effectively reduce the cost of renewable sources due to their potential for carbon mitigation. While it is possible to obtain relatively cheap energy from renewable sources, more expensive energy is required to meet existing demand. It therefore seems that the price to users should not be constant, but should increase with usage; this would help to reduce the cost of energy for those least able to afford it.

The high sensitivity to cost restrictions for achievable power from solar panels means that both subsidies and investment in technology would be particularly valuable, with advances in conversion efficiency, lifespan, production methods (Pala *et al*., 2009) and reduced land rental all able to vastly increase the viability of solar power. This would further decrease the role of bioenergy at a global scale.

This study has emphasized the challenges of decarbonising the use of energy and the adoption of land-based renewables. Key areas for further research include the reduction of cost per unit of energy of solar and wind power, increasing their lifespan and reducing their embedded carbon. Bioenergy, while limited in global output, could be important for well-distributed small-scale energy use. Furthermore, since land available for growing bioenergy feedstocks is a major limiting factor in its production, the exploitation of bioenergy should focus on uses that produce the highest net energy per unit area of land. It therefore follows that research should focus on plant breeding and agronomy that produces the largest yields per unit area.

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