An assessement of global energy resource economic potentials

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Abstract

This paper presents an assessment of global economic energy potentials for all major natural energy resources. This work is based on both an extensive literature review and calculations based onto natural resource assessment data. Economic potentials are presented in the form of cost-supply curves, in terms of energy flows for renewable energy sources, or fixed amounts for fossil and nuclear resources, using consistent energy units that allow direct comparisons to be made. These calculations take into account, and provide a theoretical framework for considering uncertainty in resource assessments, providing a novel contribution aimed at enabling the introduction of uncertainty into resource limitations used in energy modelling. The theoretical details and parameters provided in tables enable this extensive natural resource database to be adapted to any modelling framework for energy systems.

Keywords: Global energy resources, Climate change mitigation, Energy resources, Economic potentials

1. Introduction

Energy policy decisions for the planning of new energy generation capacity designed to respond to future demand require information regarding the engineering feasibility and the requirements of such systems in terms of capital investment and the availability of natural resources. Meanwhile, future energy systems are expected, in many contemporary policy frameworks, to evolve towards their gradual decarbonisation, in order to decrease anthropogenic interference with the climate system (see for instance Edenhofer et al., 2010). From an energy perspective, the decarbonisation of the sector involves a transfer of supply from traditional fossil fuel based technologies towards low GHG emission energy generation capacity such as renewable energy systems or nuclear reactors. Such a transfer requires changes in the technologies used through substitution processes, a subject extensively studied in the past (Grubler et al., 1999; Marchetti and Nakicenovic, 1978; Mercure, 2011a). However, these transformations also require changes in the use of primary energy sources. Realistic energy scenarios of the future can only be designed in a way that does not exceed natural sources and flows of energy which are available in all regions of the world. Therefore, assessments of the potential of natural energy resources are essential to energy planning and policy.

Meanwhile, many models exist that generate scenarios for the evolution of global energy systems in the future [For a recent review of IMAGE/TIMER, MERGE, E3MG, POLES and REMIND see Edenhofer et al. (2010)]. Such models, in order to generate scenarios that are realisable, must take into account the limits to each type of natural resource. However, while some energy models do not currently take explicit account of resource flows and their limits, most of them do not consider uncertainty on their limits to energy resources. Of particular interest in this work is the Energy-Environment-Economy Model at the Global level (E3MG), a macroeconometric model of the global economy, which calculates economic activity in 42 industrial sectors within 20 regions of the world (Barker et al., 2006; Koehler et al., 2006; Barker and Scrieciu, 2010; Dagoumas and Barker, 2010). In a previous paper, a new subcomponent designed for use in E3MG was introduced, modelling the trend of investor behaviour in the power sector facing the choice of various technologies, using their levelised cost of electricity production (LCOE), which includes the cost of natural resources, and the resulting technological substitutions (Mercure, 2011a,b). In this model, the limitation of natural resources occurs through the use of cost-supply curves, requiring a complete set for each type of natural resource considered in order to properly constrain the model.

Several studies have been written previously that review what was known at their time of publication of global energy potentials (UNDP, 2000; IPCC, 2007; BGR, 2010; IPCC, 2011d; WEC, 2010; Krewitt et al., 2009; WWF, 2011). These studies are useful for energy planning or modelling only as rough guides, since without exploring underlying individual economic structures associated with energy resources, and, omitting to clarify the concept of *economic* potentials, natural resource potential values can become misleading. As the key for strategic energy planning lies precisely with the cost structure of the exploitation of energy resources, such assessments are of limited use for modelling or policy-making.

Every energy source is limited, either in its total amount consumed, for stock resources, or in the total energy flow it can produce at any one time, for renewable resources. Resources tend to be exploited in order of their cost of extraction. As con-

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sumption gradually progresses to higher and higher levels of exploitation of particular resources, additional units consumed tend to incur increases in production cost. Therefore, the economic potential is better defined as a *function* of cost, rather than as a constant value. As the costs of production increase with the levels of use, developers increasingly seek alternatives, where they exist, through an evaluation of the opportunity cost. Thus, the economic potentials for energy resources within a market depend onto one another and cannot be determined individually without context, and may vary geographically as well. In particular, as resource use evolves, these economic potential values change with time, an effect that has repercussions onto the costs of energy production, and therefore onto the opportunity cost for every natural resource.

As discussed by Mercure (2011a), the economics of energy resources can be expressed in a simplified manner using a complete ensemble of cost-supply curves, which express the cost of resources at various levels of exploitation. In such a framework, the marginal cost of energy production using every individual natural energy resource may be compared using a framework such as the LCOE at every level of natural resource use, in order to enable comparisons to be made. Furthermore, the potential depletion of resources becomes naturally represented since, in the framework of cost-supply curves, the cost diverges when the total technical potential is reached, generating appropriate limitations to resource use in the model. Cost-supply curves for global resources of wind, solar and biomass energy production sites have been calculated previously using the land use model IMAGE 2.2 by Hoogwijk (2004); Hoogwijk et al. (2004, 2005); de Vries et al. (2007) and Hoogwijk et al. (2009), and are used in such a way in the TIMER energy submodel. Additionally, global cost-curves for fossil fuels have been produced by Rogner (1997), an influential work which is unfortunately becoming increasingly dated. However, no comprehensive global assessment of all major energy resources which provides an underlying cost structure currently exists in the literature.

Additionally, assessments of natural energy resources inherently possess high uncertainties, which must be taken into account in order to generate confidence levels in model outputs. For instance, the global bioenergy potential has been estimated to lie between around 310 to 660 EJ/y by Hoogwijk et al. (2005), between 0 and 650 EJ/y by Wolf et al. (2003) and between 370 and 1550 EJ/y by Smeets et al. (2007). These particular uncertainties stem from future projections of food demand and levels of technology advancement in the agricultural sector. Similarly, uncertainty arises with known amounts of stock resources, such as uranium and fossil fuels, where various levels of confidence are associated with various quantities. These uncertainties originate directly from the cumulative amount of effort that has been deployed to discover new geological occurrences, and express the fact that it is never possible to know with certainty the detailed composition of the crust of the Earth. Using a review of literature, it is possible, and appropriate, to define ranges of energy potentials rather than strict values, which dissociates the work from the specific assumptions taken in individual studies.

This work proposes a methodology and a theoretical framework for building natural resource assessments readily useable by modellers, by using a combination of cost-supply curves and a treatment of uncertainty. This methodology is then applied to produce a cost-quantity analysis for every major natural energy resource, those with a potential larger than 10 EJ/y. As part of this work, cost-supply curves were produced for 13 types of resources for every one of the 20 world regions specified in the E3MG, and form a new sub-model for natural resource use and depletion. It can, however, be adapted to any other particular aggregation of regions. For the sake of presentation in this paper, the cost-supply curves were aggregated into global curves. Since detailed disaggregated data could not realistically be provided here, tables of parameters are provided in the supplementary material that enable to reconstruct the cost-supply curves for a set of 14 world regions that were considered the most useful for the international modelling community. Additional resource specific information regarding theoretical derivations, additional methodology and justifications are also provided.

This work follows consistently a theoretical methodology that can be reused as presented by the modelling community. Therefore, clear and unambiguous definitions of concepts are first given followed by a concise description of the approach, detailing the cost-quantity analysis of resources with the associated uncertainty. Following this, a theoretical characterisation of the statistical properties of resource occurrences is given in order to enable the use of functional forms for interpolating resource data. This methodology is then used to produce cost-supply curves for renewables and stock resources. A summary of all major energy resources is given in the last section.

2. Definitions

Definitions are given here for all main concepts used in this work. Justifications and explanations for these particular definitions are given in the following section.

Natural energy resources Natural sources of energy that may be found in one of two forms: *stocks*, where energy may be extracted from fixed amounts of geologically occurring materials with specific calorific contents; *renewable flows*, where energy may be extracted from continuously producing onshore or offshore surface areas with wind, solar irradiation, plant growth, river flows, waves, tides or various forms of heat.

Theoretical Potential Total quantity of energy occurring in particular natural processes, disregarding the technical recoverability of such energy quantities.

Technical potential Total quantity of energy resource occurring in particular natural processes recoverable using specific techniques, disregarding the level of technical difficulty and the associated costs.

Economic potential Quantity of energy resource occurring in particular natural processes that are recoverable at exploitation costs that are competitive compared to all alternatives. Since the competitiveness of cost levels change with time and on the costs of alternatives, the economic potential corresponds to a quantity function of cost. However, it can be used more conveniently when expressed as a marginal cost function of the quantity used, the cost-supply curve.

Cost-supply curve Function of the cost of energy resource flow or stock, given that a certain quantity is already in exploitation or already consumed (the *marginal cost*). In this work, the cost-supply curve and the economic potential are associated to the same concept.

Uncertainty range Range of quantities defined here such that actual real observed value have a 96% probability of lying within it. This would correspond to two standard deviations, 2σ, if the distributions were normal, but they are in general skewed. Real values have a 2% probability of occurring below the range, and a 2% probability of lying above.[1]

Hierarchical resource distribution Statistical type of natural resource distribution in productivity space, with productivity values that strongly depend on the number of simultaneous positively contributing factors. Producing units of this statistical type within one particular kind of resource (wind, rivers, mines, etc) possess widely different productivities which can be ranked and cannot be exchanged for one another.

Distribution for nearly identical resources Statistical type of natural resource distribution in productivity space in which resource producing units possess nearly identical productivity values, which do not depend on the simultaneous occurrence of several factors. Producing units within one particular kind of resource (for instance plots of land suitable for solar or biomass energy production) have nearly identical properties and can be exchanged for one another.

3. Methodology

3.1. Economic potentials

Natural occurrences of energy resources are found in different forms, with varying productivity levels or require various levels of effort for their extraction, which enable their transformation into usable energy with different levels of profitability. These variations together lead to particular distributions of costs for their utilisation. Naturally, resources with the best qualities for energy production, and thus lowest extraction costs, are likely to be considered first by energy firms under financial constraints. Therefore, deriving economic potentials for energy resources involves the task of classifying and ranking different occurrences of specific resources in order of cost.

Information on energy resources is scarce and irregularly distributed, possibly inconsistent, and thus must be organised and classified in order to produce a consistent and complete set of economic potentials. Data may be patchy and incomplete, in which case assumptions are required in order to interpolate through missing parts. Such assumptions are taken in this work in the form of functional forms for the ranking of resources in terms of their cost of extraction. These are derived theoretically from basic statistical properties of resources. They have been carefully verified against several sets of data for specific types of natural resources which do not take any assumptions over the distribution of resources (wind, solar, two types of biomass resources as well as with uranium). They have been assumed to hold true for all other types of resources (for fossil, geothermal, hydroelectric and ocean resources).

Methods of assessment differ and produce different results or ranges of results. In the absence of justified criteria onto which to base a choice of particular studies over all others, resource assessments must be considered equally, the collection of which can be used to generate uncertainty ranges. This allows to decouple this work from specific assumptions used in specific studies.

The methodology presented here builds upon the approach defined in earlier work (Mercure, 2011a). The economic potential of resources is defined using the cost-supply curve, which expresses the quantity of resource available for any cost value considered *economic*, or competitive with all other alternatives. Such curves are derived from cost rankings of resources and resulting distributions. The cost variable, however, stems from varying levels of technical difficulty for extracting resources, or alternatively, the productivity of energy producing resources such as plots of land, mines, oil wells, rivers, etc. Therefore, continuous distribution functions for the amounts of resources available in nature are defined in terms of their productivity. Two empirical forms for these distributions are defined and used throughout. Confidence ranges are derived from uncertainty analysis. The combination of both is used to construct probability densities for the location in the cost-quantity or cost-flow planes where the real cost-supply curves would be situated if it were possible to determine them with certainty.[2] These probability distributions may be used as inputs to uncertainty analysis (such as Monte Carlo simulations) in energy systems modelling.

3.2. Cost-supply curves

The calculation of cost-supply curves requires rankings of energy stocks or flows in terms of cost. Costs, however are associated with the quality of resources, in other words the productivity of the resources or with the technical level of difficulty associated with their extraction. The ranking of resources in terms of their productivity can be done using histograms of the quantity of energy units that can be obtained within various ranges of productivity values. The productivity variables may be converted into costs, which result in new histograms representing the amount of energy that can be produced at costs within various cost ranges. This is shown in figure 1 *a*), with a typical distribution of energy resources, which decreases at low cost values due to the decreasing number of resources of exceptional quality, and to high cost values due to the decreasing productivity or recoverability of the resources. The shading is a representation of the confidence over their availability. The dark grey distribution shows the lower range of assured

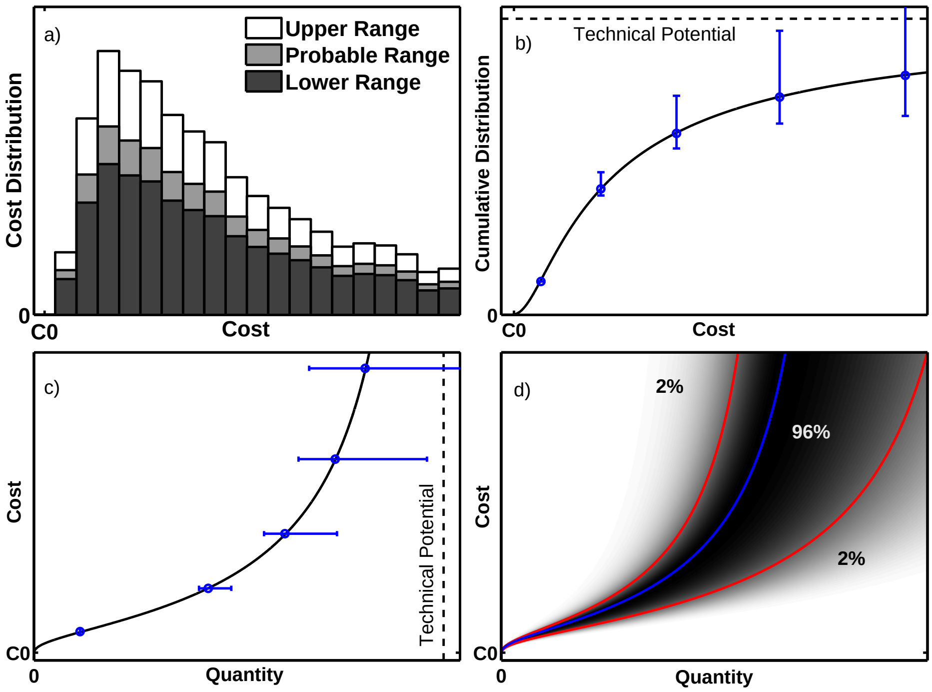

Figure 1: *a*) Sketch of a hypothetical distribution of cost ranked amounts of energy or energy flow units available in various cost ranges. The uncertainty over the amount available in each cost range is indicated with a colour shading: the dark histogram represents the minimum amount which has a probability of 98% of being exceeded, the white histogram the maximum amount associated with a probability of 2% of being exceeded. The most likely amount is represented in grey. *b*) Cumulative distribution of energy resources, with uncertainty shown as vertical error bars. *c*) The marginal cost, or cost of extracting an additional energy or energy flow unit given that a certain quantity has already been exploited, commonly called the cost-supply curve, with uncertainty represented as horizontal error bars. *d*) Cost-supply curve defined as a probability distribution, where the red curves indicate assumed limits of a 96% confidence level region in the cost-quantity plane, while the blue curve corresponds to the most probable cost-supply curve. The assumption is therefore taken that there is a 2% chance that the cost supply curve lies below the upper boundary, and a 2% chance that it lies below the lower boundary.

resources, assumed to be available with a probability of 98%. The white histogram represents the upper range of speculative resources, those assumed to be available with a probability level of 2%. The most likely total amount of resources lies between these extremes, shown in light grey.

The amounts in each cost range thus possess an uncertainty.[3] In order to determine the quantity that can be obtained at or below certain cost values, the cumulative distribution function is calculated, shown in panel *b*). This sum converges towards the technical potential. The uncertainty increases approximatively cumulatively with increasing cost values through the root of the cumulative sum of the squares of the individual uncertainty values, shown with blue error bars.

The marginal cost of resources, or the cost of extracting an additional unit of resource given that a certain number have already been used, corresponds to the inverse of the cumulative sum, shown in panel *c*). Thus, the cost of additional units diverges when the number of units used approaches the technical potential, at the point of resource depletion. Using the uncertainty ranges, or error bars, to define two additional curves, assumed to delimit the upper and lower 2% confidence limits, a probability density can be defined in cost-quantity space for the location where the real cost-supply curve would lie if it were possible to know it with certainty. This is shown in panel *d*), where the red curves delimit the uncertainty range, or 95% confidence level region, and the blue curve is the most probable of all possible cost-supply curves, the mode of the distribution. Such probability densities are normally skewed, since the uncertainty over undiscovered resources lies at higher quantity values.[4] Note that the uncertainty is assumed to vanish at the contemporary position in the cost-quantity plane, since current costs and levels of exploitation are well known.

3.3. Distributions

Natural resources are scattered around the planet in different forms with different probabilities for the cost of their exploitation. Complex processes underlie the formation of these distributions, however, they may follow certain statistical trends, the nature of which stems from the nature of the resource. One particular property affects significantly these statistical distributions, whether units of resources tend to be identical or have very similar properties, which makes their hierarchical ordering difficult, as opposed to resource types which have strong ordering. This can be expressed in terms of the degree of similarity of resource occurrences as they occur in nature. For example, solar energy can be produced using photovoltaic (PV) panels, and these panels may be installed with equal ease almost anywhere, and scarcely populated regions of similar solar irradiation will have large potentials for solar energy situated within very narrow cost ranges. In such areas, plots of land for solar produc-

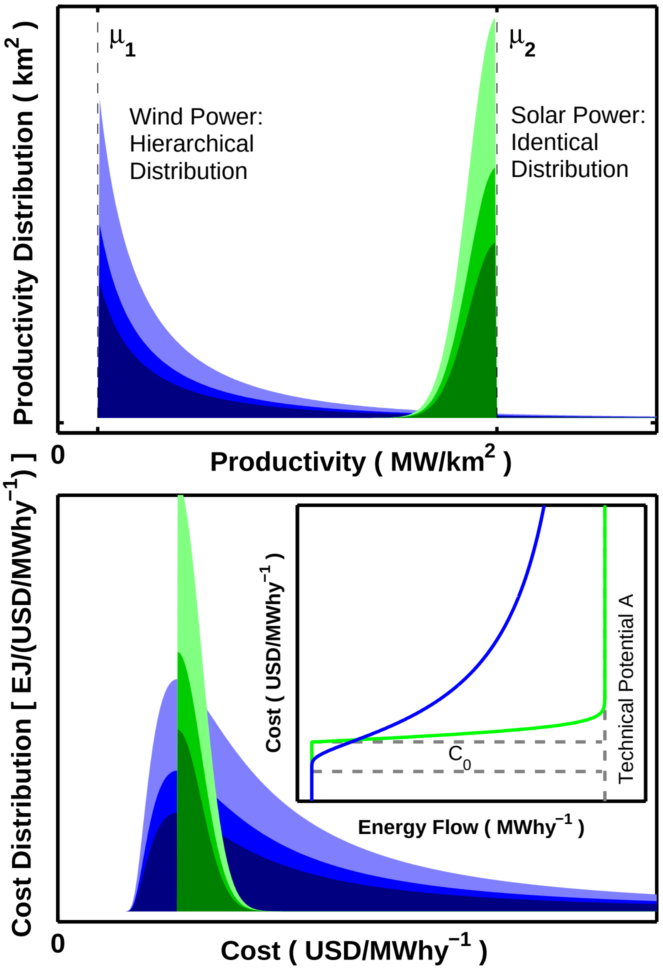

Figure 2: Depiction of two types of natural resources, based on their statistical properties. *Top*. A typical sharp distribution for nearly identical resource types is shown in green, while the broad blue distribution is for hierarchical resources, from equations (1) and (2). Both are expressed in terms of productivity. Different colour shadings represent uncertainty, as in panel *a*) of figure 1. *Bottom*. Same distributions expressed as functions of cost, from equations (5) and (4) through equation (3). Associated cost-supply curves are given in the inset. Note that the technical potential was adjusted to be the same for both curves for visual clarity.

tion are nearly identical and perfectly interchangeable for one another. The properties of wind energy potentials follow a very different structure. Plots of land within a geographical region are unlikely to possess the same average wind speed, and can therefore be ranked in order of productivity, and thus of cost for the production of wind power. As opposed to solar energy sites, wind power production sites are inherently hierarchical and non-interchangeable.

Resource distributions for nearly identical resource units are sharply defined in a narrow range of productivity, but cut off at a maximum value, which corresponds to the best possible conditions for energy production. Small variations below this maximum originate from reductions in the suitability factor of the land. Meanwhile, resources of the hierarchical type occur in large numbers in low productivity ranges, and in lower amounts as productivity increases. This property stems from the large number of positively contributing factors which are required simultaneously in order to produce an occurrence with high productivity. Such a property results in a distribution that decreases exponentially with increasing productivity, but cut off below a certain low productivity value, where it is simply assumed that no energy can be obtained with any reasonable amount of effort. This is shown in figure 2, top panel, where a typical distribution for nearly identical resources is shown in green, and one for hierarchical resources is given in blue. Similarly to panel *a*) of figure 1, the colour shading indicates uncertainty over the amounts available.

These resource distributions are well described by the following functions:

$$f(\nu)d\nu = \begin{cases} \frac{A}{\sigma}e^{-\frac{\nu}{\sigma}}d\nu & \nu > \mu_1 \\ 0 & \nu \leq \mu_1 \end{cases}, \tag{1}$$

$$g(\nu)d\nu = \begin{cases} \frac{A}{\sqrt{2\pi\sigma}}\nu e^{-\frac{(\nu-\mu_2)^2}{2\sigma^2}}d\nu & \nu < \mu_2 \\ 0 & \nu \geq \mu_2 \end{cases}, \tag{2}$$

where ν is the productivity, A is the technical potential, σ is the width of the distribution and μ_1 is the minimum usable productivity, in the first case, and μ_2 is the maximum productivity available in the second case.

Costs are related to the productivity by an inverse relationship,

$$C = \frac{C_{var}}{\nu} + C_0, \tag{3}$$

with which the distributions can be transformed into cost-quantity space. The scaling factor C_{var} corresponds to, for instance in the case of wind, solar or biomass energy, the rent value of the land in units of currency per land area, while C_0 corresponds to the sum of costs which do not depend on the productivity, in units of currency per unit of energy produced, and ν has units energy per land area. The conversion of these distribution into the cost-quantity space is given in section S.2 of the supplementary material, where, by using an appropriate approximation in the case of nearly identical resources, yields the following simple functions:

$$f(C)dC = \begin{cases} \frac{AB}{(C-C_0)^2}e^{-\frac{B}{C-C_0}}dC & C > C_0 \\ 0 & C \leq C_0 \end{cases}, \tag{4}$$

$$g(C)dC = \begin{cases} \frac{A}{\sqrt{2\pi}B}e^{-\frac{(C-C_0)^2}{2B^2}}dC & C > C_0 \\ 0 & C \leq C_0 \end{cases}, \tag{5}$$

where A is the technical potential, B a scaling factor and C_0 a cost offset, three variables used to parameterise distributions. These functions are illustrated in figure 2, where the inset shows the associated cost-supply curves. It is observed that for a similar technical potential, the curve for nearly identical resources possesses less curvature up to very near the technical potential than those for hierarchical resources, a property that stems from their lack of ordering, and results in similar cost values for most of the resources.

These functional forms have been found to reproduce very closely the cost-supply curves calculated by Hoogwijk (2004);

Hoogwijk et al. (2004, 2009) using the land use model IMAGE, whose work does not assume any functional dependence on cost for its distributions. Distributions were calculated by producing cost ranked histograms of calculated potential renewable (wind, solar and biomass) energy flows at every point of a $0.5^\circ \times 0.5^\circ$ grid of the planet. Thus, their form originates purely from statistical properties of the aggregation and ranking of the resources modelled. Using least-squares non-linear fits, the cost-supply curves in their work were found to agree very well with one or the other of the functions given above, depending on the nature of the resources: solar energy and agricultural land are well represented by the distribution for nearly identical resources, while wind power and rest land are well represented by the hierarchical distribution. Additionally, the distribution for hierarchical resources was found to agree well with observed cost distributions of uranium as reported by the IAEA (2009). Non-linear fits of these functions to IMAGE data are given in section S.2.5 of the supplementary material.

No such global cost ranked data exist for the remaining types of natural resources that could enable the justification of the choice of distribution type. Choices of distributions were therefore taken as assumptions. Potential basins that could be created for hydroelectricity possess very individual characteristics, which makes them hierarchical. Geothermal resources, however, were treated as a hybrid mixture of the two, since good geothermal sources in active volcanic areas such as Iceland can be ranked, but large amounts of very similar sites can be found in non active areas. Stock resources however were treated slightly differently. Different oil and gas occurrences originate from very different geological processes which have no relation to one another. These resource subtypes are moreover characterised by different costs of extraction. Thus, their ranking is not expected to follow a particular functional form based on statistics. However, within a subtype, resources such as conventional oil wells or mines can be assigned specific levels of technical difficulty of exploitation, leading to hierarchical distributions. Thus, in the case of oil and gas, independent distributions of the hierarchical type were assigned to every resource subtype, such as conventional oil, oil sands, oil shales, etc. This resulted in composite cost-supply curves with complex structures. Coal, uranium and thorium resources were considered to occur in a single type of occurrence, where the distribution of uranium was found to follow well hierarchical distributions.

3.4. Uncertainty

The methodology used in this work for treating uncertainty is fundamental to this analysis of economic potentials as it allows the incorporation all available information, even when sources are inconsistent or conflicting. Inconsistencies can be found between assessments for most individual natural resources, and are the result of the use of different approaches and assumptions, which can be determinant for the technical potential values derived. This is most obvious in resources such as wind power, solar energy and bioenergy, where the total amount of appropriate land depends highly onto competing activities, making the assumptions in the evaluation of the land suitability factors the main drivers of uncertainty. Other such assumptions are world population and the associated food demand, levels of technological development and changes in agricultural productivity. Resource assessments are uncertain by nature, since it is not possible to know with certainty the complete geological content of the crust of the earth, or to predict the weather and associated wind, sunshine and rainfall with perfect foresight. Thus the comparison of ever larger numbers of natural resource assessments is the key to define ranges of confidence, and these are as important as their associated most probable potential.

This work uses a consistent methodology to define probability distributions for cost-supply curves. Three cost-supply curves are derived from resource assessment data, where two are used to delimit the 95% confidence region in the cost-quantity plane, and one taken as the most probable of all possible curves. In all plots of this work, the most probable cost-supply curves are given in blue and the 95% confidence limits are displayed in red. Uncertainty ranges are almost always asymmetric, since upper ranges are intrinsically characterised by smaller amounts of accumulated knowledge.

Uncertainty is treated differently for renewable resources compared to stock resources. For renewables, cost-supply curves were calculated and taken as the most probable curves, while the 95% confidence limits were obtained by scaling the technical potential to the limits of its uncertainty range.[5] In the case of stock resources, all resource assessments provide classifications associated with cost ranges and various levels of confidence. In these cases, three cost-supply curves were derived by assigning probabilities to uncertainty classifications, as in panel *a*) of figure 1 (i.e. reserves were assumed to exist with a 98% probability, while reserves plus all speculative resources were assumed to exist with a 2% probability). Individual methodologies for all types of resources are described in the supplementary material.

4. Renewable energy resources

4.1. Wind energy

Wind speeds depend strongly on altitude as well as on landscape topologies, the climate and the type of land cover, or roughness. In general, wind speeds increase logarithmically with elevation at low altitude (for instance Sørensen, 2011), and, for a specific elevation and geographic location, occur statistically following a well defined Weibull probability distribution which decreases both towards zero and large wind speeds (for instance Grubb and Meyer, 1993). Average wind speeds on sites useable for energy production, for instance in the United Kingdom, range between 5.1 and 9 m/s at 10m elevation, the lower boundary determined by technology and the upper limit by the decreasing supply of locations with large wind speeds (for instance Sørensen, 2011). The power density offered by land areas must be calculated using technical characteristics of particular turbines. For a particular site, one integrates over all wind speeds the product of the site wind speed probability distribution and the turbine power curve. However, a correlation exists between the yearly averaged wind speed and the number of full load hours (Abed and El-Mallah, 1997). The minimum possible distance between a turbine and its neighbours

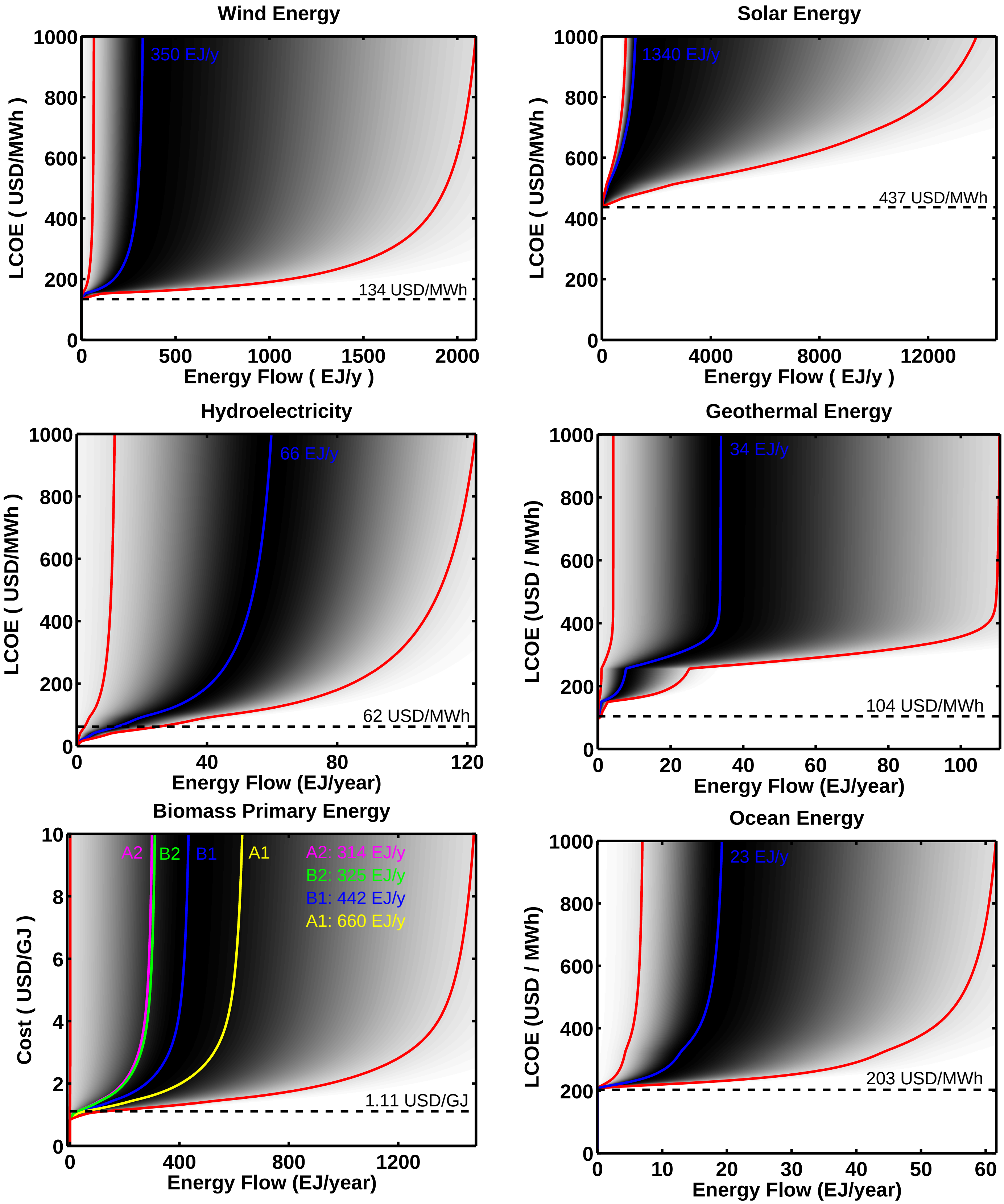

Figure 3: Cost-supply curves for renewable resources: wind power, solar energy, hydroelectricity, geothermal power, biomass and ocean energy.

in a wind farm are determined by losses produced by the wake of neighbouring turbines which results in lower wind speeds and increased turbulence, and scales with the turbine rotor diameter, limiting the density of energy that can be extracted per unit of land area (for instance Mackay, 2008).[6] Hoogwijk et al. (2004) assumed a maximum density of energy production of 4 MW/km^2.

Various research groups have calculated the global distribution of wind power (Lu et al., 2009; Hoogwijk et al., 2004; Fellows and Gow, 2000; Archer and Jacobson, 2005; WEC, 1994; Grubb and Meyer, 1993), resulting in a range of values between 72 and 2509 EJ/y for onshore wind power, and about 58 EJ/y for offshore wind power (Krewitt et al., 2009). A global onshore value of 346 EJ/y has been derived by Hoogwijk et al. (2004), in whose work, used for the present analysis, estimations of average wind speeds were applied to points on a global onshore grid, as well as the land suitability for the installation of wind farms using the land use model IMAGE 2.2.[7] Energy potentials obtained from yearly averaged wind speeds determined on every point of the grid were subsequently aggregated into various cost-supply curves for specific regions of the world, according to the land suitability factor of each point. Cost values were determined using a present value calculation including fixed and variable costs, capacity factors and energy densities associated to particular land areas.

Wind farm sites follow very strongly the distribution for hierarchical resources (see for instance the exceptional fit of figure S.4.1 of the supplementary material), since good sites with average wind speeds exceptionally suitable for energy production are geographically scattered, and the majority of areas in any region of the world possess mediocre average wind speeds, allowing a strict ordering of resource units (see for instance the map of wind speeds in Europe by Troen and Petersen, 1989). The profitability of a wind farm venture depends strongly on the quality of the wind resource, determined through capacity factor and average turbulence values. For a fixed turbine investment cost, low capacity factors increase dramatically the cost per unit of electricity produced.

Figure 3 presents the global economic potential for wind power. It gives an aggregate cost supply curve, using for the most probable curve the data of Hoogwijk et al. (2004), which involved the most detailed methodology for determining the suitability factors, resulting in a technical potential of 346 EJ/y. While Lu et al. (2009) estimated an optimistic technical potential of 2509 EJ/y by calculating wind potentials over the global onshore area and excluding low wind areas by restricting capacity factors to values above 20%, Archer and Jacobson (2005) calculated a potential of 2257 EJ/y in an assessment where the land included was restricted to class 3 wind energy sites but did not include alternate uses of the land, a value taken as the upper boundary of the uncertainty range. Meanwhile, WEC (1994) estimated 72 EJ/y based on an evaluation of the number of sites with average wind speeds above 5.1 m/s, but with an arbitrarily chosen value of 4% of that land available for wind turbine installation, in order to account for alternative land uses, taken as the lower boundary of the uncertainty range. All other existing studies result in values within this range (Grubb and Meyer, 1993; Fellows and Gow, 2000).[8]

It is to be noted that using up a large fraction of that potential results in large areas becoming covered by wind farms. Since typical individual wind turbines currently have capacities of 3 MW but capacity factors of about 25-35%, compared to 80% for coal power stations, replacing one coal power station of 1 GW for wind energy requires 700 to 1100 turbines, covering an area of 500 to 1500 km^2, compared to about 1 km^2 for the original power station[9]. Even though agricultural land used by wind farms may still be cultivated, and therefore a competition for land with agriculture does not directly occur, strong emissions reductions pathways based on substituting fossil fuels for renewables likely implies that, given the large number of wind turbines required, these would invade permanently traditional rural landscapes.

In the case of offshore wind power, although distributions of wind speeds at offshore locations tend to have a higher median, the air flow possesses less turbulence and wind speeds vary less in time, all of which contribute to produce a higher power density in terms of land area, the total area where such turbines can be installed is small compared onshore areas, unless floating turbines become widely available (Weinzettel et al., 2009). The potential of offshore wind energy is of about 58 EJ/y (Krewitt et al., 2009), approximately six times lower than the most probable potential of onshore energy given in figure 3, while its cost per unit energy is significantly higher.

4.2. Solar energy

Solar radiation over the Earth surface is of about 1.2×10^5 TW, or 3.6×10^6 EJ/y (Crabtree and Lewis, 2008). The fraction of that energy that can be harvested with existing systems has been estimated by several studies (Hofman et al., 2002; Hoogwijk, 2004; de Vries et al., 2007), and ranges between about 900 to 14800 EJ/y. Even though the total generation of energy from solar technologies has been increasing steadily during the last two decades, they still represent very low percentages in their respective categories; solar heating systems account for 0.3% of the total energy used for heating in 2008, and solar electricity generation represented only 0.06% of the total electricity generation during the same year (IEA, 2010c).

Solar energy can be harvested using either of two existing technologies, photovoltaic (PV) devices (Avrutin et al., 2011) or concentrated solar power (CSP) (ETSAP, 2010a). Single crystal silicon photovoltaic diodes currently have light conversion efficiencies of up to 25%, while III-V semiconductor cells such as GaAs systems have efficiencies of up to 28%, and solar cells using concentrated sunlight can convert light as efficiently as 43.5% (Green et al., 2011). The resulting electricity generation energy density ranges between 5 and 100 MW/km^2, depending on the type of devices used and the geographical location. On the other hand, CSP technology uses a traditional steam turbine where water was heated using sunlight concentrated with various arrangements of mirrors, and have efficiencies of around 13-24% (ETSAP, 2010a) and energy densities near 25 MW/km^2 (IPCC, 2011d). These systems are however restricted to high irradiance areas, and therefore have a lower global technical potential. Solar energy is well represented by a distribution for nearly identical resources, since within areas of similar irradiance and average cloud coverage, its cost does not depend strongly on the nature of the land, having identical productivity values that depend solely on the chosen technology, and the opportunity cost of the land is the limiting factor to its technical potential.

Figure 3 shows the global economic potential for solar energy, using PV as technology. It is an aggregation of curves determined in various world regions, based on the work of Hoogwijk (2004). The global technical potential is of 1318 EJ/y. Regional cost-supply curves were drawn from an analysis performed using the land use model IMAGE 2.2 to determine land suitability factors and the opportunity cost of the land at every point of a global grid, while regional estimates of solar irradiation were used to determine the energy potential, which have been taken here for the most probable cost-supply curve. The lower boundary curve of the uncertainty range, with a technical potential of 936 EJ/y, assumes that land availability does not increase from 2000 levels, while the upper boundary curve of the uncertainty range, with a technical potential of 14778 EJ/y, stems mostly from increases in land availability following future changes in land requirements for alternative purposes, amongst which improvements in agricultural efficiency (de Vries et al., 2007).

The use of a large fraction of the technical potential for solar energy using PV systems signifies covering up large amounts of land with solar panels. Mackay (2008) calculates an average productivity value of 10 MW/km^2 for the United Kingdom, while Hoogwijk (2004) used values between 6 and 25 MW/km^2, depending on the geographical location, with capacity factors of up to 50%. When compared to coal power plants of capacity of 1 GW and capacity factor of 80%, this implies that the replacement of one such power plant by solar panels requires an area between 50 and 500 km^2.

4.3. Hydroelectricity

Hydropower stems from water pressure gradients that are produced by the run-off of rainfall through landscape topographies, using dams to restrict water flow and accumulate water at elevation level higher than that given by the landscape, producing a potential for electricity production using turbines (see for instance IPCC, 2011b). Hydroelectricity is the most deployed renewable electricity technology, with a global installed capacity of close to 1 TW, which produced around 2% of the total primary energy supply in 2008 (IEA, 2010c). As a fraction of its total technical potential, it is also the most developed of all renewable resources, to the extent that around 23% of the global hydroelectric technical potential is currently in use. However, its exploitation around the world is not even: 25% of the European technical potential has already been developed, while Africa uses only 7% of its hydroelectric resource (IJHD, 2011).

Costs of hydroelectric systems are highly site-specific and were found to have varied between around 400 to 4500 2002USD/kW in an extensive global analysis done by Lako et al. (2003). These values are influenced by many different factors, which include material and labour costs, but also critically the opportunity cost of the land. The latter refers to the consequences of flooding large areas of land, and the resulting displacement of communities and agricultural activities, and thus varies strongly from region to region. For this reason, the deployment of hydropower is often decided on political rather than financial grounds. Hydroelectric resources were assumed in this work to follow a hierarchical distribution, since available natural basins that can be flooded possess vastly different geographic characteristics that make them unique and produces strong ordering.

Figure 3 shows the global cost-supply curve for hydroelectricity, where the dotted line indicates the cost at the current deployment of 12 EJ/y, 23% of the modest value of the most probable technical potential of 66 EJ/y, calculated in this work from data gathered by IJHD (2011). The high deployment to potential ratio is an indication that the remaining number of suitable sites for building dams is relatively limited. The intersection of this curve with the current total hydroelectricity generation value yields a cost of production of about 62 USD/MWh. However, the development of hydropower projects hardly follows an order based onto cost, but follows instead an order dictated by political considerations, which are out of the scope of this work. Therefore, this value is only indicative, and projects with LCOE values between 23 and 460 USD/MWh have been recently developed (IEA, 2010a). The use of this cost-supply curve in modelling involves the inevitable assumption of development following a cost order. In long term scenarios, this is not entirely unreasonable, since the development of the limited number of remaining available sites involves either increasing opportunity costs in inhabited areas due to increasing local populations, or increasingly large transmission costs associated with increasing distances to uninhabited areas. The cost-supply curve was derived using the theoretical, technical and economic local potential values from IJHD (2011). Since the definition of the economic potential in IJHD is not given, the (asymmetric) range of the distribution of recent cost values in the work of Lako et al. (2003) was interpreted (in 2008 dollars) as what is currently assumed economic. The remaining technical potential (above the economic potential) was assumed to involve higher costs. The upper boundary curve of the uncertainty range was derived by considering the aggregated global theoretical potential of 148 EJ/y from the data of the IJHD (2011), while the lower boundary curve of the uncertainty range was derived by assuming that no additional construction of hydroelectric dams occurs in the future, limiting future hydroelectric generation to 12 EJ/y.

4.4. Geothermal energy

Geothermal resources, stored beneath the Earth's surface in the form of heat, are heat sources constantly replenished by the radioactive decay of isotopes of uranium, potassium and thorium (see for instance Macdonald, 1959; Wasserburg et al., 1964). Although geothermal heat has been used since prehistory (Cataldi, 1993), and its utilization for electricity generation commenced at the beginning of the last century (Lund, 2005), its current deployment is small in comparison with other sources of energy. It currently accounts only for 0.3% and 4%

of the total electricity generation and heating production respectively (IEA, 2010c).

Geothermal resources are classified in four categories: hydrothermal (liquid and vapour dominated), hot dry rock (where fluids are not produced spontaneously), magma (molten rock in regions of recent volcanic activity) and geopressured (hot high-pressure brines containing dissolved methane) (Mock et al., 1997). The most commonly used type is hydrothermal, although high expectations exist regarding the development of Enhanced Geothermal Systems (EGS), oriented towards the hot dry rock type through hydraulic stimulation (Tester and Anderson, 2006). According to estimations made by Aldrich et al. (1981) based on the report of EPRI (1978), the estimated geothermal heat accumulated under the continental masses to a depth of 5 km depth is of approximately 1.46×10^8 EJ, most of it assumed to be stored in rocks and water, with a proportion of 6:1 in favour of the former. Even though this is a vast amount of heat, only a small part of it is recoverable for productive purposes.[10]

While geothermal resources are available all over the world, their accessibility differs from site to site according to various technical characteristics including the geological structure of the ground and the depth and type of heat reservoirs. In the vicinity of tectonic plate boundaries, narrow zones characterised by significant volcanic activity (so-called volcanic belts), geothermal gradients are particularly high, between 40 and 80 °C per km of depth, enabling the extraction of high temperature geothermal resources. On the other hand, areas with low volcanic activity are characterized by low and uniform geothermal gradients: around 25 °C per km of depth (EPRI, 1978; Aldrich et al., 1981). The extraction of geothermal resources in active areas are highly site-specific (Pasqualetti, 1983), and thus were assumed to follow a distribution for hierarchical resources. Meanwhile, geothermal gradients in the rest of land masses have very similar properties and costs, and were therefore assumed to follow a distribution for nearly identical resources. Cost-supply curves were produced for both types of land and both hydrothermal and EGS technologies, generating four curves which were subsequently aggregated in each world region.

Stefansson (2005) found a high correlation between the number of active volcanoes in a particular region and the estimate of the size of hydrothermal resources for electricity generation in the same region. Therefore, using the total number of volcanoes active in the world, discarding those located on the sea floor or in arctic regions, he estimated a global potential for hydrothermal energy of approximately 200 GW (6.3 EJ/y). Using this information, along with the statistical analysis between wet and dry systems developed by Goldstein et al. (2009), Bertani (2010, 2012) estimated the total geothermal technical potential to 1200 GW (34 EJ), including hydrothermal as well as EGS technologies.

The global aggregation of curves yields the cost-supply curve presented in figure 3. The associated global technical potential of 34 EJ/yr, involves a 95% capacity factor. Cost values were obtained from IEA (2010b). The lower and upper boundaries of the uncertainty range, of 4 and 111 EJ/y, are explained in section S.3.4 of the the supplementary material.

4.5. *Bioenergy*

Bioenergy, energy derived from plants, is currently the most widely exploited renewable energy resource, with 51 EJ/y, 10% of global annual primary energy use (IEA, 2010c). The combustion of biomass derived fuels is nearly carbon neutral if CO_2 uptake during plant growth is taken into account, minus losses occurring in transformation processes. Thus, biomass based technologies provide an important emissions mitigation potential. While biomass combustion using integrated gasification combined cycle technology (BIGCC) is expected to become the most efficient biomass based electricity production method (Rhodes and Keith, 2005), the combination of biomass and carbon capture and storage technology has been shown to produce negative CO_2 emissions (Gough and Upham, 2011), thus providing the potential for *reductions* of atmospheric CO_2 concentrations, or for compensating other emissions. Moreover, the emissions factors of some power plants using conventional coal technologies are being be reduced by co-firing coal and biomass fuels. Meanwhile, liquid biofuels derived from biomass, such as ethanol and biodiesel, have the potential to replace oil-derived transport fuels with minimal changes in vehicle internal combustion engine technology and jet engines (IPCC, 2011a).

Biomass currently used for electricity and biofuel production largely originates from forestry and agricultural residues, and other forms of commercial or household mixed solid waste (MSW). However, volumes of waste available, between 30 and 100 EJ/y, are low in comparison to the total potential (Hoogwijk et al., 2003; Smeets et al., 2007). The larger share of bioenergy potential lies with the production of dedicated biomass crops. Global technical potentials for primary bioenergy range between 0 and 1550 EJ/y (Wolf et al., 2003; Hoogwijk et al., 2005; Smeets et al., 2007; de Vries et al., 2007). Bioenergy crops include perennial woody short rotation coppiced trees, such as willow, poplar or eucalyptus, perennial grasses such as miscanthus, elephant grass and switchgrass, starch rich crops such as wheat, corn, sugar beet and cane, and oil rich crops such as rapeseed and palm. Depending on their nature, they can be transformed into energy carriers by using, among many processes, combustion, gasification or anaerobic decay for electricity production, fermentation or the Fischer-Tropsch process for transport fuel production (IEA Bioenergy, 2009).

Biomass production for energy purposes makes use of agricultural land and thus may have a high opportunity cost. The technical potential that lies in agricultural land is large, but energy production from biomass is in direct competition for land with food production, a situation which has the potential to drive significant increases in world food prices (Dornburg et al., 2010). Following the methodology of Hoogwijk et al. (2005, 2009), Smeets et al. (2007) and Wolf et al. (2003), the explicit assumption is taken in the present work that future bioenergy production uses no more than leftover land after the global food demand has been met, a premise that is difficult to justify in the absence of specific legislation and further investigations, but it avoids the complex problem of simulating food and biomass prices.[11] Thus the bioenergy potential is obtained by subtracting from the total biomass potential the amount required by the food demand, based on population growth curves and dietary assumptions.

Hoogwijk *et al.* evaluated the use of the land at each point of a global grid yearly up to year 2100 using IMAGE 2.2, in which leftover agricultural land was termed 'abandoned land'. The reported cost-supply curves were observed in the present work to follow a distribution for nearly identical resource units using non-linear fits of eq. (5) to their data. In addition to agricultural land, however, other types of geographical areas with lower productivities exist which can be used for particular bioenergy crops. These were labelled 'rest land' by Hoogwijk *et al.* and contribute a significant global technical potential. They were found to follow the distribution for hierarchical resources by using fits of eq. (4) to their data. Examples of such fits are given in section S.2.5 of the supplementary material. Land use depends strongly on assumptions regarding world population, diet habits, global urbanisation and trade of agricultural products. The four main IPCC (2000) scenarios, A1, A2, B1 and B2, were taken as assumptions for all exogenous variables in these calculations, and results are presented for each. Large differences arise between scenarios, with technical potentials ranging between around 314 EJ/y for the A2 scenario to 660 EJ/y for the A1 scenario, which result in large uncertainties for values of the global biomass technical potential. However, other ranges have been estimated, with more pessimistic projections of 0 to 648 EJ/y by Wolf et al. (2003), and optimistic values of 367 to 1548 EJ/y by Smeets et al. (2007). The low end of the range given by Wolf *et al.* stems from high projected food demand and low agricultural productivity, while the high end is due to mostly vegetarian diets and high productivity. Meanwhile, the high end of the range of Smeets *et al.* originates from 'super high' agricultural productivity, high availability of the land and landless animal production systems.

Figure 3 presents the global economic potential of bioenergy in terms of primary energy before conversion to electricity or liquid biofuels, derived from the data of Hoogwijk et al. (2005, 2009); Smeets et al. (2007); Wolf et al. (2003), using both abandoned and rest land. Four cost-supply curves are given, calculated by Hoogwijk et al. (2009) for the A1, A2, B1 and B2 SRES scenarios, shown as solid curves. A value near zero was taken for the lower boundary of the uncertainty range, consistent with the low end of the range calculated by Wolf et al. (2003) while the high end of the range calculated by Smeets et al. (2007) was taken for the upper boundary of the uncertainty range. For a decarbonisation scenario, the cost-supply curve derived for the B1 SRES scenario was considered the most probable cost-supply curve, but for other types of scenarios, choices of curves consistent with particular working assumptions should be made.

4.6. Ocean energy sources

The term ocean energy denotes renewable energy produced using seawater as a resource, where unlike for wind energy or hydroelectricity, not only the kinetic energy of seawater can be used to produce electricity, but also temperature gradients in the ocean and salinity differences near river mouths. Using ocean energy as a general classification type, it can be divided into four main sources of energy (ETSAP, 2010b; IPCC, 2011c):

Technology	Min. EJ/y	Mode EJ/y	Max. EJ/y	Study
Wave	6.3			Sims et al. (2007)
Energy		18.9		WEC (1994)
			65	UNDP (2000)
Tidal	1.8			Hammons (1993)
Energy		3.6		Hammons (1993)
			7.2	WEC (1994)
Total	**8.1**	**23.6**	**72.2**	
Ocean	3.2			Charlier and Justus (1993)
Thermal		32		Charlier and Justus (1993)
Energy			85	Nihous (2007)
Salinity	5.8			Skramesto et al. (2009)
Gradient		7.2		Krewitt et al. (2009)
Energy			83	Cavanagh et al. (1993)
Total	**17.1**	**62.8**	**240.2**	

Table 1: Technical potentials for different types of ocean energy used to define the cost-supply curve. The uncertainty ranges are defined using the *Min* and *Max* values, while *Mode* represents the most probable value.

- **Wave energy**, driven by transfers of energy from the wind to the surface of the ocean,
- **Tidal energy**, driven by the rise and fall of sea levels due to gravitational forces (tidal range) and the resulting water currents,
- **Ocean Thermal Energy**, driven by temperature gradients between upper and lower ocean layers,
- **Salinity Gradient energy**, derived from salinity gradients between ocean and fresh water at the mouths of rivers.

Section S.3.6 of the supplementary material provides a review of theoretical potentials for these sources, resulting in a total that could be as high as 523 to 619 EJ/y. Technical potentials however are much lower and uncertain, since the current development status for ocean energy technologies excluding tidal is preliminary, and cost data is in some cases unavailable. Specific geographical and configurational requirements for tidal and salinity gradient technologies involves, as it is the case for hydroelectricity, calculating the technical potential by summing the potential values from a large number of individual studies. Such studies have not been performed exhaustively on a wide scale yet. Meanwhile, wave and ocean thermal are based onto global extrapolations carried out using physical measurements. Global energy potentials calculated in various studies are given in table 1, and additional details are given section S.3.6 of the supplementary material.

Energy potentials for ocean thermal and salinity gradient energy are theoretical and highly uncertain, and no reliable cost estimates were found. These types of resources were therefore not included in the present calculations for the most probable cost-supply curve, due to the risk of generating misleadingly optimistic potentials given the lack of reliable information.[12]

Wave and tidal systems are better established. Therefore, using cost values found in ETSAP (2010b) and IEA (2010a), a cost-supply curve for ocean energy based on an aggregation of separate cost-supply curves for wave and tidal energy was produced, and is given in figure 3, with a small technical potential of 23.6 EJ/y. The lower and upper boundaries of the uncertainty range were obtained from the extremal values of 8 and 72 EJ/yr respectively given in table 1.

5. Stock resources

5.1. Fossil fuels

As it occurs with all types of exhaustible natural resources, fossil fuel resources and reserves are known to continuously expand, even though they are gradually consumed. This is due to periodic resource discoveries and improvements in the methods of extraction. Therefore, what is considered economical to extract changes every year. Reserves are distinct from resources, the former referring to the resources that are known to exist with almost complete certainty and to be economical to extract, while the latter refers to those which are thought to exist with various degrees of confidence, and those currently thought too expensive to extract. As technological improvements and additional knowledge affect the economics of different methods of extraction, there is a flow from resources towards reserves, and thus reserves expand (Mckelvey, 1972; Rogner, 1997). Meanwhile, discoveries continuously add to resources. As the prospection for hydrocarbon sources remains very active, this makes the production of cost-supply curves more difficult than for renewables, since is at best a snapshot in time of what is known to exist and recoverable with current technology.

In order to assess global energy potentials, it is nevertheless necessary to explore cost-supply curves for fossil fuels, even if they are derived from current knowledge, and therefore expected to change in the future. It is unlikely that fossil fuel resources turn out smaller than what is currently expected to exist. On the contrary, it is probable that they turn out significantly larger as methods of extraction are devised for types of occurrences which were until recently not thought possible to use, such as gas hydrates or oil shales. Therefore, the cost-supply curve uncertainty ranges are highly asymmetric. The associated extraction costs, which increase as low cost conventional sources are depleted, nevertheless decrease due to technological improvements, and it is therefore not immediately obvious whether costs are likely to go up or down in the future.

Global cost-supply curves have been calculated previously by Rogner (1997). These results have been used extensively by the energy modelling community; however they are becoming increasingly outdated. This section provides an update to the work of Rogner, but using an approach emphasising uncertainty, and thus, following the spirit of the current treatment of renewable resources, in opposition to the approach of Rogner, the results of this section should be interpreted as ranges rather than specific values.

The economic potentials of fossil fuels are given in figure 4, showing in order liquid hydrocarbons, gaseous hydrocarbons, hard and soft coal, the last two being classified using their calorific content.[13] For oil and gas, different types of occurrences considered in this assessment are indicated with text. These are associated with independent distributions of the non-interchangeable type, summed together to produce the total curve. Due to the wide use and global diffusion of fossil fuel extraction technology, extraction cost ranges were assumed to be the same for all regions of the world. In the case of coal, less information was found over differing types of mines and associated costs, and single distributions were used, where costs were assumed to vary little with the amount extracted. This is unlikely to matter in the long run given the very large scale of the resource, and limited expectations of its depletion.

Uncertainty ranges were determined using resource classifications, and in some cases where this is unavailable, their nature. Oil occurrences from WEC (2010) and BGR (2010) are classified as either reserves or resources, with the exception of oil shales, which are as a whole considered resources only. Four types of oil resources were considered, conventional (crude) oil, oil shales, oil sands and extra-heavy oil. Cost ranges were taken from IEA (2008). Gas occurrences follow a similar trend, but a larger number of types of resources were considered: conventional gas (BGR, 2010), shale gas (EIA, 2011), tight gas (BGR, 2010; UNDP, 2000), coalbed methane (Boyer and Bai, 1998) and methane hydrates (Boswell and Collett, 2011). The associated cost ranges were obtained from ETSAP (2010c). Large amounts of methane are known to exist dissolved in aquifers (UNDP, 2000), but were not included due to the lack of reliable data. Information for coal was derived from a mixture of data from BGR (2010) and WEC (2010). Complete details on the methodology underlying these curves, as well as region specific data tables can be found in the supplementary material.

5.2. Fissile materials

Five sources of fissile materials for nuclear reactors are known to exist. These are enumerated in order of cost. The first comes from stocks of highly concentrated ^{235}U (uranium) or ^{239}Pu (plutonium) originating from decommissioned nuclear arsenals diluted with ^{238}U. The second source is lightly enriched ^{235}U/^{238}U produced from mined natural deposits. The third originates from U and Pu recovered from spent fuel (using the PUREX process (Bonche, 2002)). The fourth source is thorium (Th) using the ^{232}Th/^{233}U fuel cycle. The fifth source is U which occurs in very low concentrations in seawater. Producing a cost-supply curve involves creating a scenario for the nuclear sector, and requires careful consideration of uncertainty. Additionally, if ingenious use of fast reactors is invoked for the future, fuel efficiencies of up to 50 times larger could be obtained, altering dramatically these expectations.

In order to construct a cost-supply curve for U and Pu, the nuclear industry was assumed to continue to use current methods and thermal reactors, and therefore, only fuels originating from naturally mined U and from nuclear arsenals were considered. Many authors stress that deposits of Th worldwide are three times larger than those of U (Bonche, 2002; Sinha and Kakodkar, 2006; Abu-Khader, 2009; Suess and Urey, 1956). However, less prospection efforts have been carried out and as

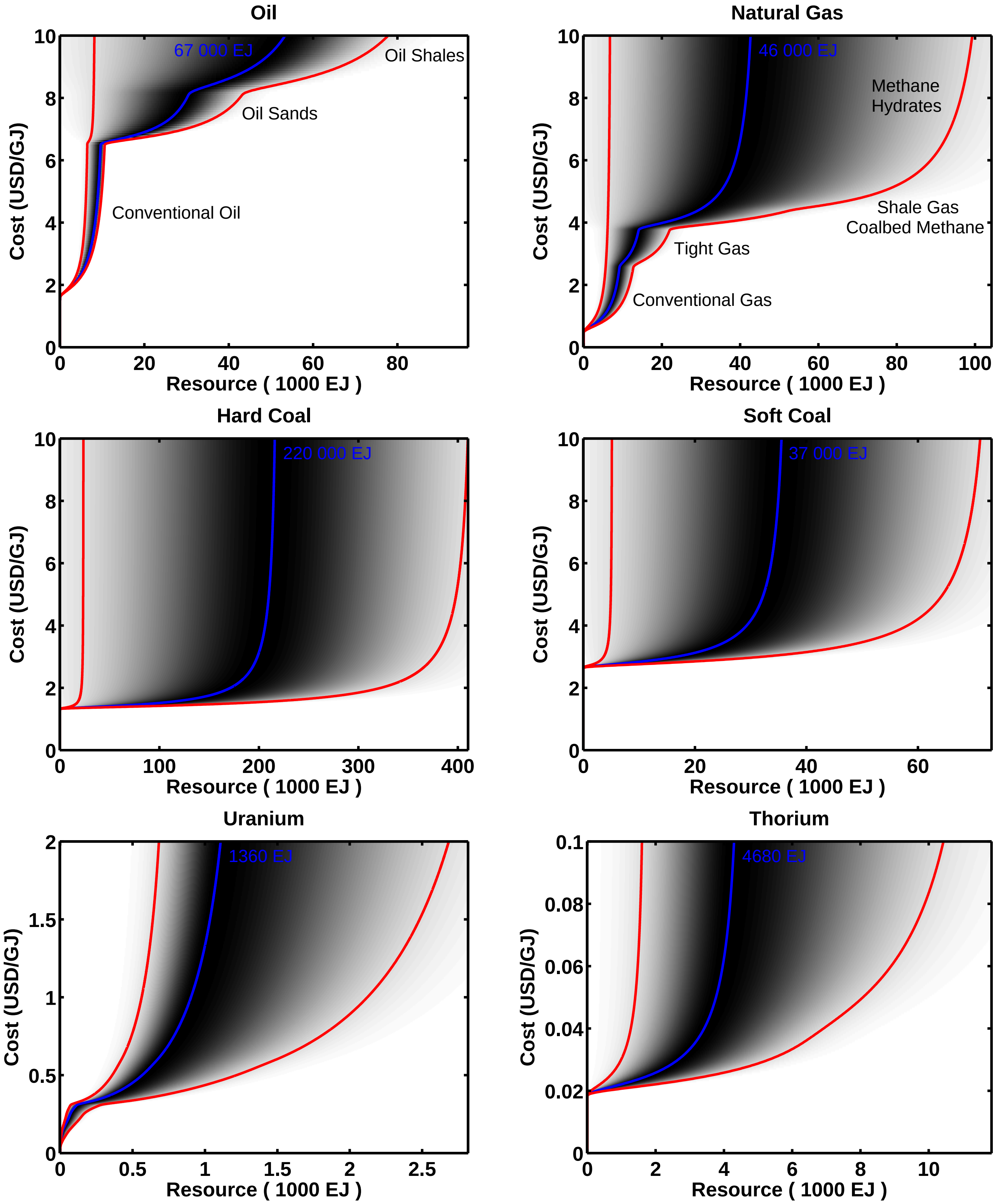

Figure 4: Cost-supply curves for fossil and nuclear resources, including oil, gas, hard coal, soft coal, uranium and thorium. Hard coal includes anthracite and bituminous coal, defined as coal with a calorific content above 16 500 kJ/kg. Soft coal corresponds to sub-bituminous coal and lignite, and includes all coal with a calorific content lower than 16 500 kJ/kg.

a consequence, the current reasonably assured reserves of Th, in tonnes of natural Th, are lower than those of U (IAEA, 2009), a situation which is likely to change if interest in Th grows. The nuclear fuel cycle for Th being more efficient than that of thermal reactors based on U, it leads to larger amounts of energy per tonne of natural Th and thus leads to lower fuel costs per unit of energy. Costs only include the extraction costs given by the IAEA, without the inclusion of enrichment or transformation components.

Detailed resource data from IAEA (2009) for naturally occurring U and Th were used to construct two cost-supply curves and associated uncertainty ranges. The data are classified into four levels of certainty and four cost ranges. Such resources generally increase naturally in size with increasing costs of extraction, as well as with uncertainty, an effect produced by the hierarchical ordering of natural resource consumption and by the decreasing amount of effort which has been spent on prospection for resources more and more difficult to exploit. For the conversion of resources from tonnages to energy values, an average conversion efficiency for thermal U reactors of 159 TJ/t was used, determined from the 2008 electricity production of 2611.1 TWh from a global fleet capacity of 273.7 GW, with a capacity factor of 80%, which used 59 065 t of natural uranium (IAEA, 2009). Meanwhile, the burnup rate for Th reactors was derived from the value of 24 000 MWd/t reached by the experimental Indian model (Sinha and Kakodkar, 2006), equal to about 2100 TJ/t. Panels e) and f) of figure 4 present the resulting global economic potentials for U and Th. Uncertainty ranges for U were obtained by considering only reasonably assured reserves (RAR) for the lower boundary of the uncertainty range, RAR and inferred reserves for the most probable cost-supply curve, and all of the RAR, inferred, prognosticated and speculative resources for the upper boundary of the uncertainty range.

The uncertainty ranges are highly asymmetric due to the tendency of the size of speculative resources to increase with the level of uncertainty. It is observed that in terms of energy, reserves of Th are larger than those of U, and that these are also less expensive per unit of energy, due to the higher burnup rate of the Th system. It must be emphasised that U resources could, in principle, be used with much higher burnup rates, were fast reactors to be deployed globally. The resources of U do not include seawater U, as data over these are scarce and highly speculative[14]. Finally, it is to be noted that the fuel component of the levelised cost for nuclear reactors is very small compared to the investment costs, which results in very small influence of the fuel costs onto the decision-making, unless nuclear resources are depleted.

6. Summary of energy resources

Table 2 provides a summary of all types of global energy resources, classified by type (renewable flows or stocks), to which a type of statistical distribution it is assigned (for hierarchical or nearly identical resources, or a hybrid mixture of both), along with technical potential values. The potential values are given with their lower and upper boundaries of the uncertainty ranges. For comparison, current consumption of these resources is given based on data from IEA (2010c).

Resource			Use	Technical Potential			
Name	Type	Dist.	EJ/y	L	M	U	Units
Wind	Flow	Hierarch.	.72	72	350	2257	EJ/y
Solar	Flow	Identical	.04	936	1340	14778	EJ/y
Hydro	Flow	Hierarch.	12	12	66	148	EJ/y
Geotherm.	Flow	Hybrid	0.23	4	34	111	EJ/y
Biomass	Flow	Hybrid	51	0	442	1548	EJ/y
Ocean	Flow	Hierarch.	.002	8	23	72	EJ/y
Oil	Stock	Hierarch.	170	9	67	98	10^3EJ
Gas	Stock	Hierarch.	109	7	46	106	10^3EJ
Hard Coal	Stock	Hierarch.	139	24	220	419	10^3EJ
Soft Coal	Stock	Hierarch.		5	37	75	10^3EJ
Uranium	Stock	Hierarch.	30	0.83	1.36	3.43	10^3EJ
Thorium	Stock	Hierarch.	-	1.74	4.68	12.27	10^3EJ

Table 2: Summary table for all energy resources. $Stock/Flow$ indicate whether resources are renewable flows or stocks. $Hierarch./Identical/Hybrid$ identifies the type of statistical distribution assigned. Use refers to current yearly consumption of these resources. L indicates the lower boundary of the uncertainty range. M indicates the most probable technical potential. U indicates the upper boundary of the uncertainty range.

7. Conclusion

This paper presents an assessment of global economic energy potentials for all major energy resources, those with a potential larger than 10 EJ/y. These were given in the form of cost-supply curves, adding an economic structure to energy potentials, and therefore providing an unambiguous definition of the economic potential. Additionally, these are given using a probabilistic construction that allows a simple representation of uncertainty. The curves were calculated using assumptions over the cost distribution of resources using functional forms based on statistical properties of resource types. The set of energy potentials include six types of renewable energy sources, wind, solar, hydroelectric, geothermal, biomass and ocean energy, as well as four types of fossil fuels, oil, gas, hard and soft coal, and two nuclear materials, uranium and thorium. While the potentials for renewable resources were determined predominantly based onto an extensive review of the literature, potentials for stock resources were determined directly using resource and reserve assessment data.

The cost-supply curves calculated in this work were produced for the benefit of the global energy modelling community, for the purpose of constraining models of the energy sector in order to produce realistic scenarios of future energy use. It is hoped by the authors that this work will supersede outdated studies currently used and provide a consistently calculated update for all types of energy resources. In particular, the large set of regional cost-supply curves underlying the aggregate curves presented in this paper form the core of a new model for natural resource use and depletion for the global E3 model E3MG, to be used through the family of technology models FTT. Other regional aggregates can be provided by the authors.

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Notes

[1]The 2σ probability range correspond to erf($\sqrt{2}$) = 95.45%, yielding 2.28% as a probability of values occurring above or below the range. The values of 96% and 2% are used instead for convenience.

[2]Note that the use of uncertainty ranges in the cost-quantity/cost-flow plane relaxes the constraints of using specific functional forms, since it allows variations in the particular forms of the functional dependences within the ranges.

[3]No error bars are present for the cost variables, since an uncertainty in costs signifies an uncertainty in how to distribute energy units between cost ranges, which translates into an uncertainty in the number units in each range.

[4]Thus, the most probable cost-supply curve is neither the mean or the median of the skewed distribution, it is the mode, or maximum.

[5]This is done in order to avoid inconsistencies where curves calculated independently, for instance by fitting data, could in some cases cross.

[6]While larger turbines intercept a larger wind front, they are also spaced further apart in two spatial directions. Thus, while the power production of large wind farms scales with the square of the length of the blades, it scales inversely with the square of the distance between turbines. These two effects almost cancel each other out, except for the fact that taller turbines intercept higher wind speeds at higher altitudes.

[7]For details on IMAGE see Bouwman et al. (2006).

[8]Fellows and Gow (2000) concludes with an estimate for 2020 of 148 EJ/y, while Grubb and Meyer (1993) calculated a global potential of 191 EJ/y.

[9]The variation originates from both assumed ranges in capacity factors of 25-35% and turbine densities of 2.2 to 4 MW/km^2 (Mackay, 2008; Hoogwijk et al., 2004).

[10]Note that the average replenishment of the geothermal heat underground is several orders of magnitude inferior to the stock of heat currently available: around 65 mW/m^2 at the continental level, producing an average thermal energy recharge rate of about 315 EJ/yr (Pollack et al., 1993). This value can be considered as the theoretical potential of geothermal energy if viewed in terms of sustainable extraction of geothermal resources over an extended period. However, the amount of time over which geothermal resources could be used at higher rates than this is likely to be more than one thousand years.

[11]Bioenergy potentials could in principle be larger if global food demand is not met. However, it will not be lower if global food demand is indeed met. The problem of simulating food prices is complex as it involves modelling both local food markets, underreported in developing countries, and efficiency changes associated with changes in food prices.

[12]The costs for ocean thermal and salinity gradient energy systems are likely to be much higher than those of tidal and wave energy. This would result in a piecewise cost-supply curve featuring an additional step at high costs.

[13]Hard coal includes anthracite and bituminous coal, while soft coal includes sub-bituminous coal and lignite, the last two having lower calorific contents than the first two. The limiting calorific value used to separate the two categories is of 16 500 kJ/kg (BGR, 2010).

[14]U is present dissolved at very low concentrations in seawater (3-4 ppb, from IAEA (2009)), giving rise nevertheless to large amounts of U given the size of the terrestrial body of seawater. Water turnover due to currents is very slow however, making it highly speculative whether a significant portion of seawater U can be recovered, and the costs involved are very high (Bonche, 2002).

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