Sustainable power density in electricity generation

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Abstract

Purpose: When comparing renewables with fossil fuels, emotional approaches are fuelled by the difficulties in defining a proper metric able to make consistent comparisons among energy sources. In literature several approaches have been proposed, all effective in some way but ineffective in others. Variables like energy density, prices, estimated resources, life time emissions, water use and waste, all come at the same time to form an unmanageable mix. This paper discuss the adoption of a shared metric to clarify the boundary conditions that limit the solutions can be operated and to define which scenarios are sustainable and which are not.

1. Introduction

In discussing the pros and cons of different energy technologies for electricity generation, the lack of a shared metric makes difficult the comparison among them and emotional approaches prevail. Variables like energy density, power density, prices, estimated resources, life time emissions, water use and waste, all come at the same time to form an unmanageable mix. In literature several approaches have been proposed, all effective in some way but ineffective in others. Among them, EROI (Energy Return on Energy Invested), Net Energy and EPBT (Energy Payback Time) (Murphy & Hall, 2010) are the most popular, but many others, like Doubling Time and Energy Intensity Ratio (EIR) (Ioannis Kessedes, 2011), are also meaningful investigation tools. These indexes calculate the gain factor of the various energy systems considered as a whole. Most stress on the economic viability, while others stick to the energy balance and yet others highlight the importance of including differences in energy quality or the availability of critical materials. Differences in estimates result from how system boundaries and consequently energy inputs and outputs are defined. Still, in all these metrics, there is something missing in the picture. Basically, the difficulty is that the pros and cons of each solution are hard to be represented, the price issues apart, in a single parameter. Furthermore, all these performance indicators do not incorporate externalities and finiteness of the resources available. While difficult, the adoption of a shared metric would greatly facilitate comparison among different solutions and scenarios. However, even if recognized as a critical issue (Mann, 2013), little can be found in literature beyond the economic or footprint assessments (Curran, 2013). A more comprehensive approach is needed and this paper support the view that power density, as proposed by Smil (Smil, 2010), is the most powerful parameter in evaluating the variety of energy technologies and moreover, it highlights what is the key limitation in natural resources exploitation, the amount of available land.

2. Energy vs power density

Difficulties in comparing different sources of energy come first from their intrinsic different dimensions. At the same time, physics dimensions are the clue for their classification, in two types:

- Volumetric sources, i.e. fossils (oil, gas, coal), uranium, hydro dams and biomass. For fossils and uranium, different units, like barrels, cubic meters or tons, are used to measure available reserves and estimated resources but all share the fact that they are mined volumes of materials and are subject to depletion. Once they are mined, they can be moved where and when they are needed, to provide the essential base load of any modern electric infrastructure.

- Flowing sources, comprise solar (PV, thermal and concentrated), run-of-the-river hydro, wind, marine waves and currents, gravitational tidal, geothermal. All are measured in watt per square meter or per meter. These resources are not subject to depletion but they cannot be moved and are definitely limited in power, continuity and spatial distribution with some differences among them. For example, geothermal has its flow of energy coming from the earth, it is discontinuous in spatial distribution but constant in time, therefore geothermal can always be available *when* it is needed but, like the solar and wind, it is not always available *where* it is needed.

In the rest of the article, volumetric sources will indicate only fossils and nuclear because biomass and hydro dams actually are something in between. Biomass, for example, is a volumetric source, resulting from stored solar energy as any fossil, and can even substitutes coal in power plants. On the other side its time constant of replenishment, years rather millions of years, compared with the Earth carbon cycle time scale, makes it a renewable source. The same apply to hydro dams which make use of water with residence time, defined as the average time required to completely renewing a waterbody's water volume, of weeks or months (Maneux, et al., 2001) depending on the input and output flow rate in cubic meters per second. This brings to recall that renewable energy is a source of energy that can be used and replenished naturally in a relatively short period of time. Non-renewable energy is energy that cannot and it is subject to run out.

It comes as no surprise that in the case of volumetric sources the attractiveness is measured by the energy density (energy per unit volume, J/m^3) while in case of flowing sources is given by the power density (energy per time unit per unit area, $J/s/m^2$). The two differences in physical dimensions highlight that making use of renewable sources is a real time intercepting of energy flow, for example from the sun or from the center of the earth, while making use of volumetric sources is the exploitation of energy previously stored.

Because dimensionally different, the limitations in the exploitation of the two types of energy sources are also different. In general there are three types of limitations. The first could come from the *tout court* unavailability and makes a resource inadequate simply because it runs out. Second limitation could come from the power density, because a very low rate of supply could make the source unusable in most of the applications. Third is sustainability. Abundant and usable energy is needed for present needs but also for future generations and therefore long term consequences of resources exploitation needs to be carefully considered. Discussion on these three possible limitations comes before of any economic assessment and it is the ground where it must be based.

3. Finiteness of energy reserves vs production vs population

By definition, volumetric sources are subject to depletion. In order to address this concern, several studies have been carried out and periodic updates are available over the amount of fossil reserves or estimated resources. How finite an exploitable source is, it depends on the level of consumption compared with reserves. In literature this is expressed by the reserves-to-production ratio (R/P). The R/P value appears to be, for the combination of oil (54 years), gas (63 years) and coal (112 years), between 50 and 100 years (BP, 2012). It is widely recognized that the level of production P is strongly dependent on economic growth while the reserves R value depends on economic factors like price of oil plus possible technological breakthroughs. Definitely the incertitude in both the single R and P values are big but, at the same time, R/P provides the order of magnitude of the depletion concern and roughly shows how the present consumption is not a negligible part of the available resources.

A different, much less common but yet meaningful figure, is also the ratio reserves-to-population, which provides the amount of reserves available per person. Based on the same data (BP, 2012), this comes to be something around 1 GWh per person[1] which compared with an average 10 MWh consumption of primary energy per year per person, gives another version of the same 100 years time window. This finiteness is much more compelling if it is taken into account that fossil reserves are supposed to be shared not only with the present but also with the future population, which may reclaim its share of fossils for the multitude of needs they are able to satisfy. The non-energy use of fossils is already today around 10% (Kroll, 2013), a privilege which could be lost forever in the future. That makes the available volume per person approaching to zero and would make burning fossils, yet for this reason, unsustainable *per se*. The conclusion is that fossil volumetric resources are limited in absolute value, limited to some tens of years given the present level of energy consumption and limited to nearly zero if they are thought to be shared with future generations.

Should the same considerations apply to nuclear power? Are the uranium reserves in such an amount that finiteness poses a meaningless threat? Would have the breeder technology, capable of generating more fissile material than it consumes, succeeded, nuclear option would constitute yet today, waste concern apart, a nearly unlimited source. This is not the case and if the R/P value is taken into account, based on the evaluation given in the latest edition of the Red Book (OECD Nuclear Energy Agency (NEA), 2010), total identified uranium resources will last for over 100 years at current consumption rates, as in the case of fossils. Then, both the volumetric resources, fossil and nuclear, provide a similar time window.

The same discussion does not apply to flowing resources as they are unlimited by definition. This is very good news but is very well balanced by other elements seen in the next paragraph.

4. The 10 W/m^2 cap in power density

If the attractiveness of volumetric sources is measured in J/m^3, and their potential in supply is given in m^3, on the other side, both the attractiveness and the technical potential limit of renewable is measured in W/m^2 $^($J/s/m^2), the power density. The solar flow of energy at Earth's surface provides a power density of about 1 kW/m^2. Combining the efficiency conversion, seasonal and daily cycles plus accommodation constrains, it comes out that a reduction of a couple of order of magnitude is needed and in the case of PV system it results something like 10 W/m^2. This value could be taken as the starting point of any evaluation of renewables being the best value of power density achievable today, and other solar renewable options, like biomass or tidal or even wind, are below this value (MacKay, 2009). To understand how heavy is the burden of this limitation it is useful to remind that from domestic appliances to car engines (and not considering a multitude of more demanding industrial applications) daily life is used to deal with kW, two orders of magnitude higher.

That said, the question becomes how to compare the energy density of fossils with power density of renewables. Does it make any sense to talk about power density for fossils? Yes indeed. In recent years several studies (Vasilis Fthenakis, 2009) have been carried out highlighting how volumetric sources are yet mined but a life cycle assessment (LCA) shows that a considerable amount of land, correlated with the amount of energy produced, is needed and therefore it makes sense calculate a “LCA power density” also for them.

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[1] 36 ZJ (estimated reserves)/ 3600 (conversion J to Wh) / 7 10^9 (world population)

On this track Smil has already proposed power density, expressed in W/m^2, as the most universal measure of energy flux able "…*to evaluate and compare an enormous variety of energy fluxes from natural flows and exploitation rates of all energy sources (be they fossil or renewable)* …". In his

Technology	Gagnon / Bertani 2005 (Geothermal)		Fthenakis		McDonald (2030)		Smil		Mac Kay	Selected values
	Land use as m^2/kWh	W/m^2	Land use as m^2/kWh	W/m^2	Land use as km^2/TWh/y	W/m^2	min (W/m2) (MW/km2)	max (W/m2) (MW/km2)	W/m^2	W/m^2
Biomass Crops	5,33E-01	2,08E-01	1,25E-02	8,89E+00	5,43E+02	2,05E-01	5,00E-01	6,00E-01	5,00E-01	5,00E-01
Geothermal	5,00E-02	2,22E+00			7,50E+00	1,48E+01				2,22E+00
Hydro	1,52E-01	7,31E-01	4,00E-03	2,78E+01	5,40E+01	2,06E+00			2,40E-01	2,40E-01
Wind	7,20E-02	1,54E+00	1,50E-03	7,41E+01	7,21E+01	1,54E+00	5,00E-01	1,50E+00	2,00E+00	2,00E+00
Photovoltaic	4,50E-02	2,47E+00	3,00E-04	3,70E+02	3,69E+01	3,01E+00	4,00E+00	9,00E+00	1,00E+01	1,00E+01
Coal	4,00E-03	2,78E+01	4,00E-04	2,78E+02	9,70E+00	1,15E+01	1,00E+02	1,00E+03		2,78E+02
Gas			3,00E-04	3,70E+02	1,86E+01	5,97E+00	2,00E+02	2,00E+03		3,70E+02
Nuclear	5,00E-04	2,22E+02	1,15E-04	9,66E+02	2,40E+00	4,63E+01				9,66E+02

Table 1 Land use and LCA power density calculated including mining, transport and production

study (Smil, 2010) he compares six modes of electricity generation: coal, biomass, natural gas, photovoltaic, solar concentrated and wind. For each type Smil considers the land use of the entire life cycle, from mining to transportation, from electricity production to waste management and comes to a figure of power density, W/m^2, for each technology. Results are listed in table 1. Data coming from other studies are also listed (Gagnon, et al., 2002) (McDonald, et al., 2009) with mixed results witnessing the difficulties of dealing with this subject. Data are shown in their original heterogeneous approach, with land use sometime expressed in m^2/KWh or km^2/TWh and then translated in W/m^2.

Last column of the table lists the values selected for the rest of the article. In particular the values for renewables are taken from Mac Kay (PV, wind and biomass) (MacKay, 2009) but only where not UK dependent, geothermal is taken from Bertani (Bertani, 2005), hydro and nuclear from Fthenakis (Vasilis Fthenakis, 2009). Fossils (coal and gas) are taken averaging the Smil range. Because scarcity of data and lack of standard procedures, land use estimations and the correlated power density, appear to be different among the various authors, with large error and uncertainty.

For this reason, it will be reasonable not to stick to the exact digits (nuclear in particular is expected to have the highest power density) in table 1 but rather consider the values as order of magnitudes. Values range from 0,1 W/m^2 to 1000 W/m^2 (500 Km^2/TWh to 0,1 Km^2/TWh). What appears is that fossils suffer the limitation of going depleted in 100 years but they are 2-3 of order of magnitudes better than renewables in terms of LCA power density and give sense to the present stubbornness in continuing to burning them.

In fig.1 it is shown the world land use for electricity generation by sources making use of data in table 1 and TWh produced in 2009 (International Energy Agency, 2011) (Observ'ER, EDF, Credit Agricole, 2012). Hydro is about 1.5 million km^2, 95% of total land. This figure sounds reasonable when compared with data (TWh/year and flooded area) of the top ten hydropower station listed in Wikipedia and in agreement with other estimates (David M. Rosenberg, 2000).

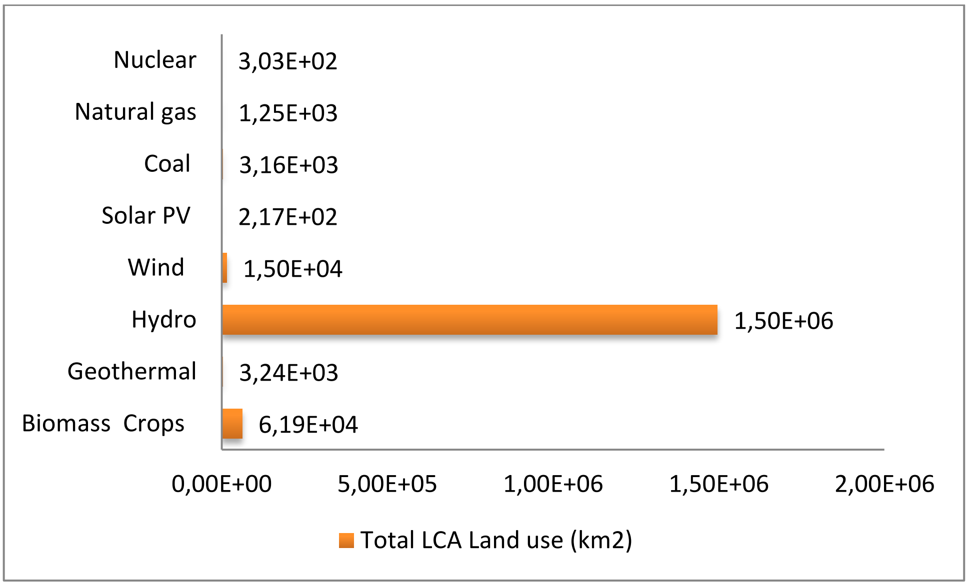

Fig. 1 Land use for the world electricity generation in 2009 (Source IEA)

5. Sustainable carbon cycle

So far limitations have been established in m^3 for fossils and in W/m^2 for renewables. It could be assumed that technological breakthroughs will improve the 10 W/m^2 upper limits of solar renewables by a factor of 2 to 5, but it will never change dramatically by order of magnitudes, having its roots in solar constant. Viceversa, it cannot be excluded a one or two order of magnitudes in change of fossil reserves volume. Would this change the picture of the energy issue over period of time? This question brings to the third limitation, sustainability. The present electricity production system, with its carbon emissions, could, someone could argue not necessarily, provoke harmful climate changes and then become unsustainable. Actually carbon is part of the earth life and its biogeochemical cycle is the way by which carbon is exchanged among different sources and sinks of the Earth. What makes sustainable a carbon cycle is the zero net difference between the anthropogenic emissions, given by burning of fossil fuels and changing of land uses, and natural sequestering processes, like the uptake of oceans via physicochemical and biological processes and the photosynthesis of terrestrial plants. In fig.2 it is shown that

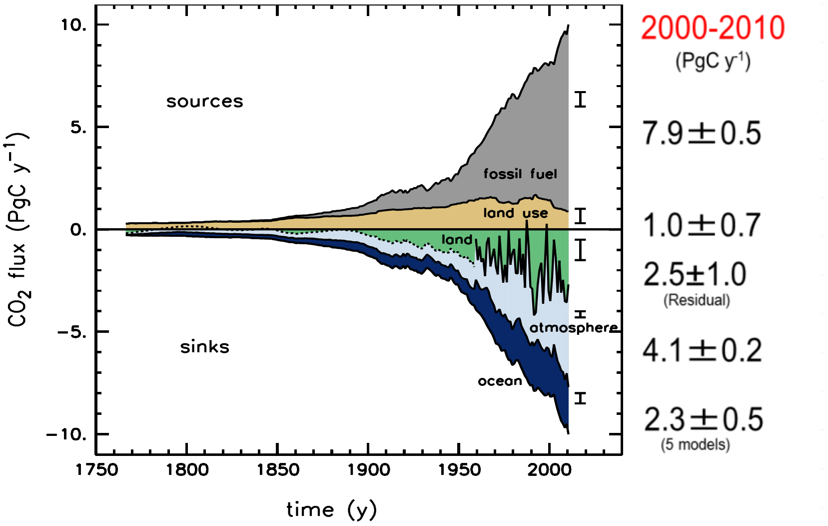

Figure 2 Human Perturbation of Emissions (source Global Carbon Project)

Human Perturbation of the Global Carbon Budget elaborated by Global Carbon Project (Le Quéré, et al., 2012) where it appears the increasing amount of carbon released in the atmosphere as effect of no zero net difference between emissions and sequestering mechanisms. Natural land and Oceans during the 1958-2010, removed more than half of all C emitted from human activities, each sink contributing in roughly equal proportion. In the same period, the size of natural sinks has grown almost at the same pace as the growth in emissions, although year-to-year variability is large. There is the possibility, however, that the fraction of all emissions remaining in the atmosphere has a positive trend due to changes in emissions growth rate and decline in the efficiency of natural sink. Would this be the case, energy policy makers will be forced to act and two options are available: cut the emissions, for example reducing the electricity generation based on fossils, or enhance the sequestering capability, notably enhancing the forest surface. In the latter case, in order to evaluate how large should be the dedicated area, it is needed to quantify the relation between the emissions associated to each TWh and the sequestering capability per km^2 of forest.

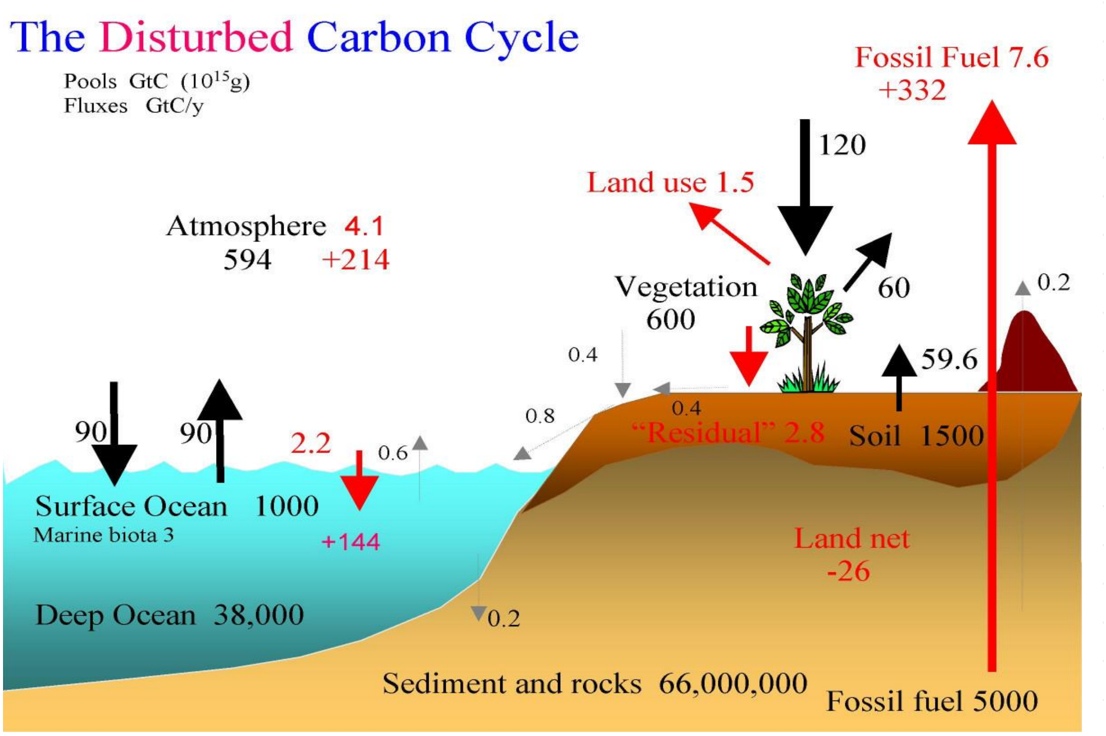

Figure 3 Global Carbon Budget (source Global Carbon Project)

5.1 Emissions sources

Fig.3 shows residence times and fluxes from the different C pools (Zeng, 2013). Emissions are expressed in C, rather than in CO_2, because this will make easier comparison with the natural carbon sinks. All data come with some uncertainty but still the latest figures published by IEA (International Energy Agency, 2012) show that in 2009, the world total emissions were about 7,9 Gt C, a total resulting from 1.6 Gt C of land use change plus 6,3 Gt C of fossil fuels burning. In this study the focus will remain on the emissions coming from combustion of fossils for electricity generation, which result to be about 40% of total world emissions. This in turn has, in 2009 (International Energy Agency, 2012) a share of 43% from coal (~3 Gt C), 37% oil (~2,5 Gt C) and 20% gas (~1,5 Gt C). Table 2 goes into details of emission values for the different energy sources in electricity generation with data from EPRI (EPRI (Electric Power Research Institute), 2011), UK

POST (Parliamentary Office of Science and Technology, 2011) and IAEA (Joseph V. Spadaro, 2000).

Technology	IAEA (2000) (kg C/kWh)		UK Post (2011)(kg C/kWh)		EPRI (2015) (kg C/kWh)	Reference values (kg C/kWh)
	min	max	min	max		
Biomass Crops			0,025	0,025		0,025
Geothermal			0,004	0,014		0,009
Hydro	0,000	0,064	0,001	0,004		0,002
Wind	0,003	0,013	0,002	0,030		0,016
Photovoltaic	0,027	0,076	0,020	0,032		0,026
Coal	0,263	0,389	0,214	0,270	0,229	0,242
Gas	0,120	0,187	0,099	0,133	0,101	0,116
Nuclear	0,002	0,006	0,002	0,007		0,004

Table 2 Emissions in electricity generation as kg C/kWh (Gt C/GWh)

Oil is rarely quoted because its contribution in electricity generation is becoming more and more marginal. Reference values for the rest of the article are calculated as average of UK Post 2011. Between fossils and low emitting sources there is roughly one order of magnitude, with the closer gap between solar PV (~ 0,026 kg C/kWh) and gas (~ 0,116 kg C/kWh).

5.2 Emissions sinks

On the side of carbon sequestering mechanisms, the ocean plays a crucial role absorbing 20 to 35 per cent of anthropogenic CO_2 emissions. Nevertheless, in making the calculations, the ocean contribution will be kept as a fixed, being not able to operate on its amplitude as sinker.

Net removal of CO_2 from the atmosphere by terrestrial ecosystems occurs when plant photosynthesis exceeds all processes of consumption and respiration, resulting in above-ground plant growth and increases in root and microbial biomass in the soil. All the land plays a role in natural carbon sequestering but the main part comes from forests which, over the past four decades, have moderated climate change by absorbing about one-quarter of the carbon emitted by human activities. A report by DoE (Reichle, et al., 1999) estimated in 1999 the potential of C sequestration of world forests at 1–3 Gt C/year out of the total potential of 5.7–10.1 Gt C/year in all biomes of the world.

	Area (Mkm2)	Total sink (Gt C / year)	Rate (tons C / km2 / Year)
Boreal forests	11,35	0,5	44,053
Temperate forests	7,67	0,8	104,302
Tropical intact forests	13,92	1	71,839
Total average intact	32,94	2,3	69,824
Tropical regrowth forests / Land use change	5,57	1,7	305,206
Total average intact	38,51	4	103,869

Table 3 Carbon sequestration rate by forests (source Pan)

This value is quite in accordance with the 2.3 Gt C per year calculated by Pan (Pan, et al., 2011), which becomes about 4 Gt/year considering also the tropical regrowth forests contribution, usually hidden in the balance of land use change. In table 3 data from Pan are calculated over 95% of the world forests and last column shows the carbon sequestration rates per km^2 among the different types of forests, and provides 70 t/ km^2 as average of intact forests and 100 t/ km^2 if tropical regrowth forests are included. The total amount of forest area is about 40 10^6 km^2, in agreement with the latest figures from FAO (Food and agricolture organization of the United Nations, 2010).

5.3 Global Carbon Budget (GCB) power density

Combining the forest sequestration rate (table 3) with the emissions/TWh from the power plants in operation (table 2), an indicative figure of the electricity generation footprint results to be: 850 km^2/coal based TWh/year (i.e. every TWh produced in one year asks for 850 km^2 of forest), 600 km^2/oil based TWh/year and 400 km^2/gas based TWh/year.

To make sustainable every TWh produced, somewhere it is needed a portion of forest which could act as sink of the associated emissions. With this approach, it is made possible discuss side effects not apart but included in a power density definition and a novel unique parameter, *the Global Carbon Budget (GCB) power density*. In table 4 values of *GCB power density* are listed.

The previous advantage of fossils in terms of power density simply disappears. Biomass results still to have the lowest value but solar PV performs a better value compared with coal and is quite the same of gas. In order to check how reasonable the results are, the world energy production of electricity in 2009 (International Energy Agency, 2011) (Observ'ER, EDF, Credit Agricole, 2012) is also listed with the share among the different sources and the resulting emissions gives a total value of 2.5 Gt C/y, roughly 40% of the total emissions, as estimated by IEA. Nuclear, which was a world apart in comparison with renewables in the LCA definition of power density (3 orders of magnitudes distance), is now still the best option but with a reduced factor of 25 compared with PV. Last column lists the amount of forest land needed to make sustainable the present electricity generation and the total land appears to be at least 20 times the land estimated with the standard life cycle analysis. Representation is given in fig. 4.

6. Nuclear energy, future land use and sustainable power density

In calculating the footprint of nuclear technology land used by power plants plus the mining area, the waste repository and the size of the respect zones has been included. The land evacuated after

	World Electricity (TWh/year) (2009)	Share of world electricity production	LCA Power density (W/m^2)	LCA Land use (Km^2/TWh)	Total LCA Land use (km^2)	Emissions (tonnes C/TWh)	Footprint (km^2/TWh)	GCB Land use (Km^2/TWh)	GCB power density (W/m2)	World Emissions (Gt C/ y)	Total GCB Land use (km^2)	Future Land Use (life time unit)	Sustainable power density (W/m2)
Biomass Crops	290,8	1,5%	**0,50**	2,28E+02	6,64E+04	2,53E+04	2,44E+02	4,72E+02	**2,42E-01**	7,37E-03	1,37E+05	1,1	2,20E-01
Geothermal	67,3	0,3%	**2,22**	5,14E+01	3,46E+03	9,26E+03	8,92E+01	1,41E+02	**8,12E-01**	6,23E-04	9,46E+03	1,1	7,38E-01
Hydro	3335,2	16,2%	**0,24**	4,76E+02	1,59E+06	2,04E+03	1,97E+01	4,95E+02	**2,30E-01**	6,82E-03	1,65E+06	1,5	1,54E-01
Wind	276,4	1,4%	**2,00**	5,71E+01	1,58E+04	1,60E+04	1,54E+02	2,11E+02	**5,41E-01**	4,42E-03	5,84E+04	1,1	4,92E-01
Solar PV	21,0	0,1%	**10,00**	1,14E+01	2,40E+02	2,60E+04	2,51E+02	2,62E+02	**4,36E-01**	5,46E-04	5,50E+03	1,1	3,96E-01
Coal	8142,3	40,6%	**277,78**	4,11E-01	3,35E+03	2,42E+05	2,33E+03	2,33E+03	**4,90E-02**	1,97E+00	1,90E+07	2	2,45E-02
Natural gas	4291,8	21,4%	**370,37**	3,08E-01	1,32E+03	1,16E+05	1,12E+03	1,12E+03	**1,02E-01**	4,99E-01	4,80E+06	1,1	9,27E-02
Nuclear	2687,4	13,4%	**966,18**	1,18E-01	3,18E+02	4,36E+03	4,20E+01	42,09	**2,71E+00**	1,17E-02	1,13E+05	2	1,36E+00
Total (oil excluded)	19112,2	95%	NA	NA	1,68E+06	NA	NA	NA	NA	2,50E+00	2,57E+07	NA	NA
Oil	1022,8	5,1%											
Total	20055,0	100,0%											

Table 4 Sustainable power density and present world electricity generation, by fuel type

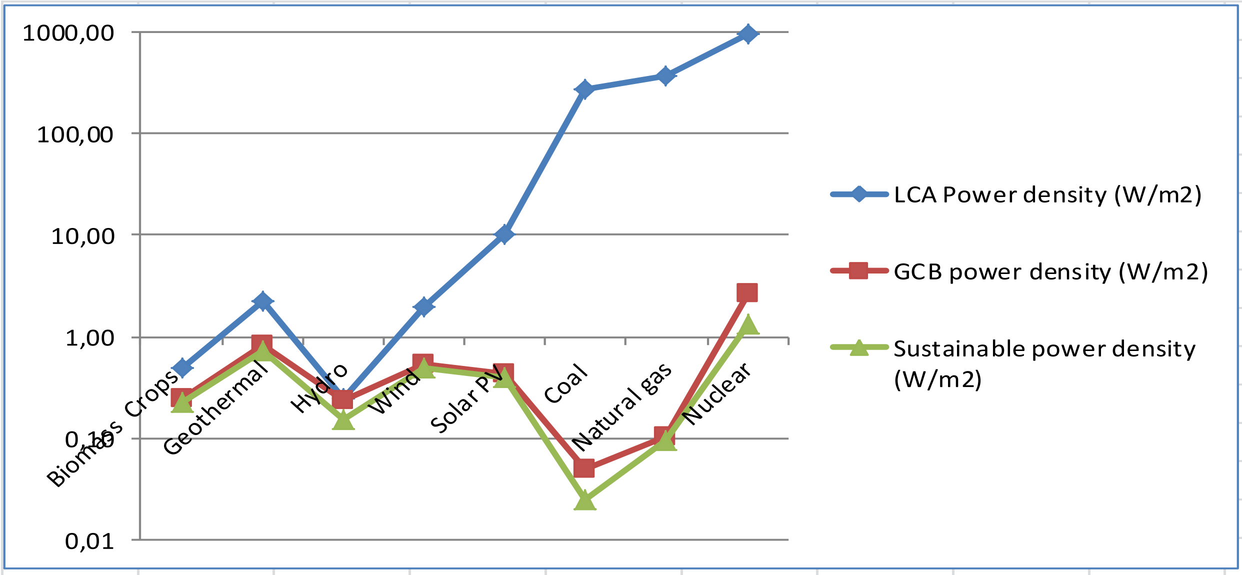

Figure 4 LCA (Life Cycle Assessment), GCB(global Carbon Budget) and sustainable power density

all the historical accidents has not been considered. An indicative value for the size of an evacuation area is 50 km radius from the accident point. For example, in Ukraine, the Exclusion Zone covers an area immediately surrounding the Chernobyl nuclear power plant of approximately 2,600 km^2

(Bondarkov & Boris Ya. Oskolkov, 2011). Multiplying this value with the probability of a disaster per TWh would have little effect to the average power density value. Effects on human health are not taken into account. Within these boundaries, data show that nuclear energy is less competitive but well placed also in terms of GCB power density. Still, what still makes uneasy with nuclear energy is not only the amount of land made unavailable to the community while power plants are running but also the lasting effects of the nuclear waste and their intrinsic capacity of sequestering land in the far future, what Fthenakis calls the “land occupation”. Time is the new physical dimension put in place by nuclear energy. From this perspective, nuclear energy poses an ethical question which could hardly be ignored. Each energy option has its own pros and cons and each society is allowed to take a decision until it is framed in its own time scale, while there is much less evidence that anybody is allowed to take decisions for the future generations, legitimate stakeholders who are unable to express their view.

This line of reasoning applies, actually, also to fossils. The use of fossils is sustainable under a threshold value determined by a neutral global carbon budget. Beyond this threshold, given the lasting effects of climate changes, it should not be allowed to go. It has been calculated that 20% of the present emission will last in the atmosphere for hundreds of years (EPA (United States Environmental Protection Agency), 2012) which is not the time scale of nuclear waste but, because the unpredictable behavior and nonlinear effects of these changes, their happening should simply be prevented. In table 4, *the future land use,* expressed in “life time” unit, is a measure of how long the land used to generate electricity will remain altered. A technology which would need a decommissioning time equal to zero will have sustainable power density equal to GCB power density, while in the case of decommissioning time equal to the running time of the plant, the GCB power density would halve. At this stage of the study, figures provided are merely an exercise. First of all, there are no enough historic data on decommissioning for most of the technologies. Secondly, the LCA power density keeps considering the total land used resulting from several sectors, with different time intervals. These difficulties will be ignored and the following assumptions will be made: PV, wind, biomass and geothermal are assumed to be low in land altering. Much more complex is the situation with hydro as the restoration of the land to the previous state would result difficult and unpredictably long. The same would be for the coal case while natural gas should be much less invasive. Finally, the nuclear case could result to be not much longer than coal, waste apart. This very rough estimations, which need to be validated by historic data, have been translated into a 10% extension of land use for bio, PV, wind, geo and natural gas plants, 50% for hydro and 100% for coal and nuclear. The resulting *sustainable power density* provides a value of how much land is used and for how long, then power density become the ratio of the total energy produced, divided all land involved and time needed to bring back the land to other uses. Most of renewables benefit from this definition of power density as they little disturb the land they use and side effects are very limited. Furthermore, land used for PV and wind could be shared with other uses: cover of buildings or agriculture. This would reinforce their competitiveness which could be represented, but not in the table, by a multiplying factor > 1 for the power density.

Last but not least, nuclear poses a further issue. The breaking into the picture of the time variable brings another threat: the loss of sensible information (NEA, 2011). Nuclear waste is thought to be stored in geological sites expected to be stable for the thousand, if not millions, years to come. All these repositories will be secured and labeled to prevent unintentional misuse. Apart the finite level of confidence in the geological stability of these sites, a major concern is also that there is no experience at all on how preserve such sensible information over a time period of million years and the most likely event is that future inhabitants of Earth will be unable to understand whatever warning signals are used to label nuclear site repositories. This alone would make nuclear energy unsustainable.

7. Conclusions

Energy density and power density are the cornerstones of the physical limitations in the exploitation of the energy sources. On this basis, a novel classification of energy sources, volumetric and flowing, has been proposed and discussed in light of three parameters: abundance, power density and sustainability. The dimensional differences, J/m^3 vs J/m^2/s, would make the two classes intrinsically heterogeneous in spite of the need of a full scale comparison of energy technologies but an extended definition of power density, based on LCA, has been proposed to compare trough a single parameter all the different options. The same approach has been taken to include emissions and the amount of land needed to act as emissions sink and the new definition of GCB (Global Carbon Budget) power density has been adopted to highlight how fossils are not that competitive compared with most of the renewables. The life cycle analysis has been extended to include not only the time window needed to generate electricity but, also the time needed to make the land available for other uses, in particular to future generations. If sustainability is included, the despairing low power density of renewable has been shown to be not that far from that associated to fossils. Also nuclear option is shown to be not anymore better by orders of magnitude. The key point in adopting this extended definition of power density is that it shows how the level of emissions the planet can sustain has not a predefined value but it depends on the sequestering mechanisms put in place and how powerful they are. Present life is in a finite planet and the finiteness of available land comes into play in several ways: into the possible depletion of volumetric sources, into the amount of land needed for flowing sources exploitation, into the carbon sequestration role of forests. A similar approach has been adopted by other scholars and, for example, water, soil, phosphorous and potassium have been identified as the key issues of coming decades (Bauer, et al., 2010) (Grantham, 2012). Actually, would the surface of the planet, with the same distribution of resources, be ten times bigger, it would be able to provide ten times the amount of water or absorb ten times the carbon emissions is able now. In the proposed extended definition of land use, power density could eventually become the universal parameter to compare the different energy options and show how limitation in land comes to be the root of all resources limitations and *sustainable power density* may be an indicator much more significant than economic ones usually used.

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