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Quantified Criteria for Electricity Generation Systems

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Abstract
Criteria of sustainability for electricity generation systems, with their indicators are hereafter presented, quantified and aggregated. An index characterizing the level of sustainability is proposed: the Electricity Production Sustainability Index (EPSI). A general application is made to the current electricity generation sources, renewable or not renewable. The results confirm the high level of sustainability of hydropower, especially run-of-river, and also geothermal and wind power. Reference is made to the researches of the Paul Sherrer Institute in Switzerland and of the International Energy Agency: program on "Hydropower and the Environment: Present Context and Guidelines for Future Action":

Introduction
In 1987 the new concept of sustainable development was presented to the general public by the Brundtland report "Our common future". This paradigm is not so evident and every one in its field of activity should try to characterize sustainability, first qualitatively, then quantitatively and if possible, facing to uncertainties, probabilistically.
The same approach happened with the prediction of energy consumption for this century, and the controversy in the field of the supporters of the soft energies, generally environmentalists, and the stakeholders concerned by the development of the level of life of the populations, became more fruitful when the quantities of energy which should be produced during this century were estimated.
The problem is clear to day: with the increase of the population of the world of 50% up to 2050 and the necessity to increase the level of life of the poorest populations, the primary energy should be multiply by a factor of 2.5 and the electricity production by a factor of 3.
On the basis of the enquiries made in the world by the International journal Hydropower & Dams, published each year in its "World Atlas & Industry Guide" (and we have to recognize, in our profession, the unique, and high value of this publication, which is a reference), we know that the remaining potential of hydropower, not only technical but also economical, will allow a multiplication of hydroelectricity by this factor of 3: the installed capacity in 2005 of 740 GW should and could be increased to a total of 2200 GW during the next 50 years (or 100 ?) ; this means, for an additional capacity of 1500 GW, an investment of around US$ 1500 billion. However this will represent only 10% 0f the primary energy consumption in 2050, and around 20% of electricity.
A very large effort should be made and encouraged to develop the other renewable energies, and perhaps we could expect to have the same contribution of 10% of the primary energy for them with geothermal, biomass, solar, wind and energy from the ocean. The remaining 80% would be thermal for a large part and nuclear if it is politically accepted.

How much will be theses energy sources sustainable? Is it possible to compare on that matter on rational criteria? Researches were made during the past 10 years and we notice three of them. In Switzerland the Paul Sherrer Institut proposed and quantified criteria of sustainability to be able to compare various energy options. Similar studies were made in Canada by Hydro-Quebec. At an international level, within the framework of a comprehensive program of energy cooperation among the countries members of the Organization for Economic Cooperation and Development (OECD) the International Energy Agency (IEA), implements, between 1995 and 2000, a program focused on hydropower and an excellent document was published under the Chairmanship of Mr. Jean-Etienne Klimpt, from Hydro-Quebec: "Hydropower and Environment: Present Context and Guidelines for Future Action".
One of the author of the present paper, exposed during the Conference on Renewable Energy organized in 2001 in Lauunceston, by Renewable Energy Generators of Australia, a list of criteria of sustainability. They were also

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published in 2001 in Hydropower & Dams World Atlas. A new step will be made here: to quantify and aggregate these criteria, for various energy generation systems and propose an Electricity Production Sustainability Index (EPSI).

2. Criteria and indicators

30 years ago, according to the UN recommendations, the objective of development was to make the greatest possible contribution to the welfare of the population and this welfare had three dimensions: social, economic and cultural. The environmental protection was not specifically mentioned, but was, for sensitive stakeholder, include in the cultural chapter. Then, during the past decades, the environmental regional and global impacts resulting of human activities took an increasing importance and it appears necessary to take also in consideration the environmental protection as an objective. Today the volets of the "sustainability triptych" are: Economic, Social and Ecological. But in addition, in the field of energy generation systems, we think that it is necessary to introduce two specific volets: Technical and Policy.

Table 1 in the next page gives the 5 Criteria: Environment, Social, Economic, Technical and Policy which are characterized by Indicators measured as much as possible by physical units. For each Criteria we propose a repartition of the weight of the Indicators, as rational as possible, to our sense. However this evaluation process, could be considered as subjective, but everyone could try to give his own assessment. We will come back later on the weight of the Criteria themselves. We give hereby some comments on reasons of the chosen Indicators.

Concerning "Environment" the objective is to avoid depletion of natural resources, to limit the use of the land and the pollution by emissions and waste, to protect landscape and biodiversity.

For the "Social" aspects, we should consider the possible impact of the energy generation system on the health of the population, during operation and in case of a major hypothetical accident. The resettlement of persons in the area of the plant should be solved in accordance with human dignity, but it is clear, that the best generation system is this one with the lower number of persons resettled. Finally the number of employments created is a social Indicator.

Indicators of sustainability for "Economic" are important: a low investment is an advantage for countries with limited finances and a low cost of energy is a powerful help for the development; the life duration of a plant is evidently a characteristic of sustainability and a long life means a long amortization time and consequently a low cost of energy produced.

Sustainability concern also "Technical" matter. Decades of experience in a technology, its low complexity and its potential of development are advantageous factors. The fact that a scheme could be developed with multipurpose objectives increases its direct and indirect benefit (for example, protection against floods). The various energy systems are not equal in flexibility to produce energy at the right time for the consumers. An intermittent generation system of renewable energy necessitates generally the support of a non renewable generation system, which decreases its sustainable character.

Finally, as for "Policy", Indicators concern the supply security, independence of the country for fuel supply and technology. For nuclear energy, the Treaty of non proliferation of nuclear weapons could limit the development of this technology in developing countries which should accept safeguards of the International Energy Agency. On that matter, we can say that the sustainability of this generation system is questionable.

3. Quantification of the Indicators

The quantification of the Indicators poses the problem of the choice of the units and the scales, having in mind the next step of the analysis which will be the aggregation of the indicators. The problem could be solve by the choice of a same unit for all the Indicators such as a monetary unit; this is possible but for some of them difficult or even impossible. We have chosen various physical units adapted to each Indicator and we will see later how to perform the aggregation.

For "Environment", the consumption of fossil energy and production of pollutants and waste are simply calculated in kg or t reported to the energy produced during all the life of the power plant or during one year; this last case allows to make difference between a base or a peak load or intermittent plant.

To be comprehensive the evaluation of consumed resources and environmental burdens, the most efficient way is to perform a "Life Cycle Assessment" (LCA) of the energy generation system: fuel production, plant construction operation, decommissioning, waste treatment.
Concerning the landscape and biodiversity conservation, analysis could be made to identify sub indicators which could be quantified, as for example number of people visiting a site or number of protected species; to be simple we have only chosen here coefficients.

Criteria and indicators	units or coefficient	weight [%]
1. Environment		
1.1 Consumption of fossil energy	kg / GWh	20
1.2 Use of land		
• during operation	km^2 / TWh/y	10
• in case of major accident	km^2 / TWh	10
1.3 Emissions		
• greenhouse gases	t equiv. CO_2 / GWh	15
• other polluting gases	t / GWh	10
• particulates	kg / GWh	5
1.4 Consumption of water	m^3 / MWh	5
1.5 Waste		
• quantities	kg / GWh	10
• containment duration	years	5
1.6 Landscape conservation	coefficient	5
1.7 Biodiversity	coefficient	5
		100
2. Social		
2.1 Resettlement	persons / MW	30
2.2 Health impacts during operation	Years of live lost / TWh	30
2.3 Employment	employees/GWh	20
2.4 Risk aversion (in case of major accident)	casualties/kWh	20
		100
3. Economic		
3.1 Investment	$/kW	30
3.2 Amortisation period	years	5
3.3 Construction time	years	10
3.4 Life duration	years	5
3.5 Energy production costs (incl. O&M)	$ cents/kWh	30
3.6 Energy Payback Ratio	kWh invest/kWh output	20
(3.6 Direct and indirect benefits and costs)	($ cents/kWh)	-
		100
4. Technical		
4.1 Experience	years	20
4.2 Degree of complexity of the plant	coefficient	20
4.3 Multi purpose scheme characteristics	coefficient	20
4.4 Energy generation flexibility	coefficient	30
4.4 Future evolution potential	coefficient	10
		100
5. Policy		
5.1 Degree of security and independence regarding		
• fuel supply	coefficient	50
• technology	coefficient	30
5.2 Risk of technology proliferation for arms of mass destruction	coefficient	20
		100

Table 1: Criteria and Indicators, units and weights for sustainable energy development regarding electric energy production systems

For "Social" Indicators the number of persons resettled is related to the power of the plant. Other Indicators are related to the energy produced during the life of the plant.
It is interesting to note that some renewable energy systems, such as wind farms, are creating an important number of employments per kWh produced during their life. The reason is that this energy produced is relatively small. By the fact that this energy is financially supported by the government, the system generates indirect costs supported finally by the taxpayers; this is not exactly an Indicator of economic sustainability. We

should notice also that we considered only the employment for the operation of each generation system but another important indicator is the number of employments in the industry of the concerned technology.
The risk aversion concerns the fear of the population of a major accident; we can quantify it by the number of potential casualties which could happen in this accident related to the production of the plant. In fact this Indicator should include not only the damages but also the probability of the accident and the plant is designed with a probability of accident as low as reasonable achievable. So the real risk is very low and acceptable, but the risk aversion is subjective; this is a fact and we should accept an irrational Indicator.

For "Economic" units are simple to define such as $/ kW or $/ kWh or years of life duration. The indirect and indirect benefits and costs could be quantified, even this is not easy. But here the most important are counted in other Criteria such as employment, landscape conservation.

Finally for "Policy" Indicators we are using coefficients; also here some researches could be developed to determine quantifiable sub indicators

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4. Aggregation of criteria

In order to be able to compare each Generation system (a_i) regarding the Weighted (p_j) sustainability Indicators (cj) an evaluation matrix is built up as follows for n Generation systems and m Indicators:

Indicators	c_1	c_2	c_3	$\cdots c_j \cdots$	c_m
weight → generation systems ↓	p_1	p_2	p_3	$\cdots p_j \cdots$	p_m
a_1	e_{11}	e_{12}	e_{13}	$\cdots e_{1j} \cdots$	e_{1m}
a_2	e_{21}	e_{22}	e_{23}	$\cdots e_{2j} \cdots$	e_{2m}
a_3	e_{31}	e_{32}	e_{33}	$\cdots e_{3j} \cdots$	e_{3m}
$\vdots$ a_i $\vdots$	$\vdots$ e_{i1} $\vdots$	$\vdots$ e_{i2} $\vdots$	$\vdots$ e_{i3} $\vdots$	$\vdots$ $\cdots e_{ij} \cdots$ $\vdots$	$\vdots$ e_{im} $\vdots$
a_n	e_{n1}	e_{n2}	e_{n3}	$\cdots e_{nj} \cdots$	e_{nm}

Table 2: Evaluation matrix for various generation options (a_i) regarding the weighted (p_j) sustainability Indicators (c_j)

For each generation system and each Indicator, we obtain an evaluation (a judgement) and it is appropriate, to aggregate all of them to obtain a global evaluation. The power generation system could then be compared between each other. On easily realizes that all is not absolute in this process, in many points subjected to individual appreciations; in particular the weighting of certain Indicators can differ when being performed by engineers, economists, environmentalists or even politicians.

Aggregation is a delicate stage. We will not enter into details here; just let us quote the three simplest methods, theoretically. The first method consists in bringing all criteria to the same unit, e.g. the costs and benefit per kWh, not only for the internal effects but also external (the external cost, also known as an externality, arises when an activity of one group of persons have an impact on another group and when that impact is not fully accounted, or compensated for by the first group). Fig. 1 shows one example illustrating the external cost estimates for electricity production for existing technologies in Switzerland. The higher the externalities the less sustainable a power generation option is.

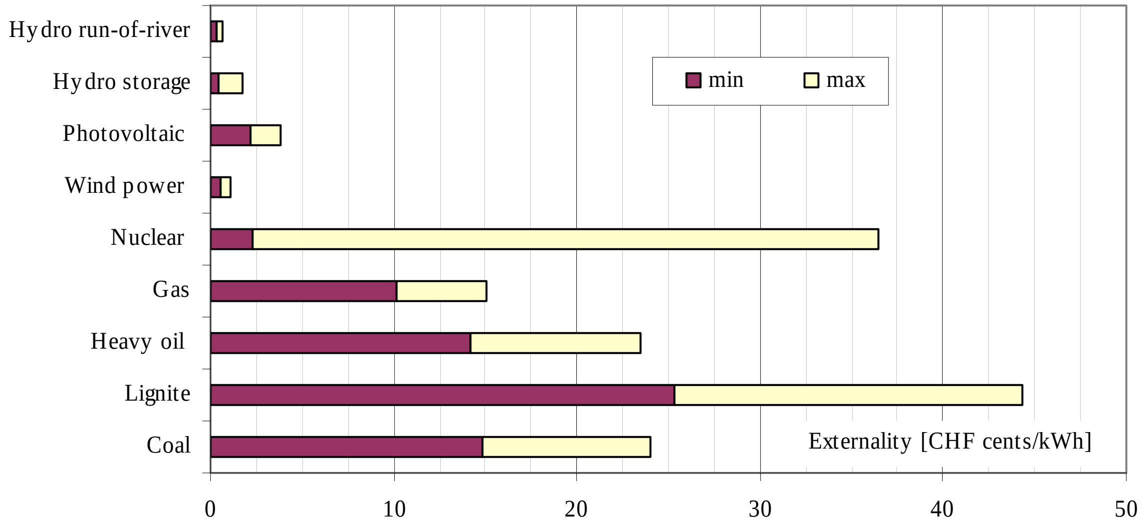

Fig. 1: External cost estimates for electricity production for existing technologies in Switzerland

Another method consists in arithmetically combining the evaluations (e_{ij}) and weights (p_i) as a straightforward weighted average of the evaluations to obtain an overall value E_i for each power generation system:

$$E_i = \frac{e_{i1} \times p_1 + e_{i2} \times p_2 + \cdots\cdots + e_{in} \times p_m}{p_1 + p_2 + \cdots\cdots\cdots + p_m} \qquad \text{(Eq. 1)}$$

The foremost disadvantage of this method is that an Indicator with a very small value, which would lead to an unacceptable installation, can be compensated by high values of other Indicator. A second deficiency results in the fact that the evaluation for an installation, concerning the various Indicators, uses only one scale which does not evolve from one Indicator to another.

Another technique consists in the multiplication of the normalized and weighted evaluations in the following way: one does not operate any more on the weighted values of each evaluation as in the preceding case (e_{ij} x p_j), but on normalized evaluations for each Indicator with a reference Indicator evaluation and we obtain for each power generation system:

$$E_i = \left(\frac{e_{i1}}{e_{11}}\right)^{p1} \times \left(\frac{e_{i2}}{e_{12}}\right)^{P2} \times \cdots\cdots \times \left(\frac{e_{ij}}{e_{1j}}\right)^{pj} \times \cdots\cdots \times \left(\frac{e_{im}}{e_{1m}}\right)^{pm} \qquad \text{(Eq. 2)}$$

Finally, this global evaluation method of each installation makes it possible to establish a classification and thus to select "the best and most sustainable" power generation system. This method has two major advantages: on one hand the elimination of the values for the evaluations with worst values criterion, and on the other hand, that we do not need an identical scale for all criteria.

In the present study, this global evaluation method has been applied. The normalization has been performed using the maximum value for each Indicator which does not need to be from the same power generation option for different Indicators. Due to this normalization method, the worst Indicator evaluation remains neutral (=1) in the calculation and weighting. Using Eq. 2, the most valuable solution has the smallest indicator.

The final Electricity Production Sustainability Index (EPSI) results from an additional normalization with the maximal value of the inverse of the evaluation according to Eq. 2. This way, the best solution has a value of 100 and the least sustainable ("the worst") technique a value close to one. This evaluation can be performed for the each of the five Criteria or globally for the whole set, each one being weighted.

5. Application to electric power generation systems

The following energy generation options are analysed:

Base- and peak load options:	Hydropower - with storage reservoir Thermal power - diesel Thermal power - heavy oil
Base-load options with limited flexibility:	Thermal power - natural gas combined-cycle Fuel cell, hydrogen from fossil fuel Thermal power - bituminous coal or lignite Hydropower - run-of-river Thermal power - nuclear Thermal power - coppice plantation Thermal power - (forestry) waste combustion Geothermal
Intermittent options that need backup generation:	Wind power Solar photovoltaic

We don not go into a detailed description of the investigated power generation option, this can be found on various sources in literature and on the Internet. The selection is based on recent investigation performed by Hydro-Québec, where all major quantified criteria can be found. According to the IEA, the following power generation options are considered as renewable: (small) hydropower; solar photovoltaic and concentrating solar power; biopower; geothermal power and wind power.

Except the technical and policy criteria subset, where only average values have been introduced, all other criteria subsets, environment, social and economic, have been analysed taking into account the range of values found in literature or base on evaluations by the authors. Therefore the possible extend of the EPSI and the average value are shown in the respective figure.

6 Values of EPSI for the single Criteria

The values of EPSI could be divided in 5 classes, creating a scale of sustainability values:

< 10 :	poor
10-30 :	mediocre
30-60 :	good
60-80 :	very good
> 80 :	excellent

Table 3 : Scale of sustainability values for electricity generation systems

The figure 2 concerns the Electricity Production Sustainability Index regarding the Environment (EPSI env) and we can make the following remarks:

- In the order of decreasing values we find: hydropower- run-of river, geothermal, hydropower-storage reservoir and wind power,
- The large range between maximum and minimum values for hydropower-storage is due to the large range in the use of land during operation and for geothermal to the comparatively small gas emission but extending over a large range, depending on the literature sources, and whether taking into account production emission only or the whole live cycle including long lasting exploration,
- All the systems using combustion are poor; the low value of waste combustion is mainly due to other polluting gas emissions as it is almost CO_2 neutral regarding forest or "green" waste as a combustion source.

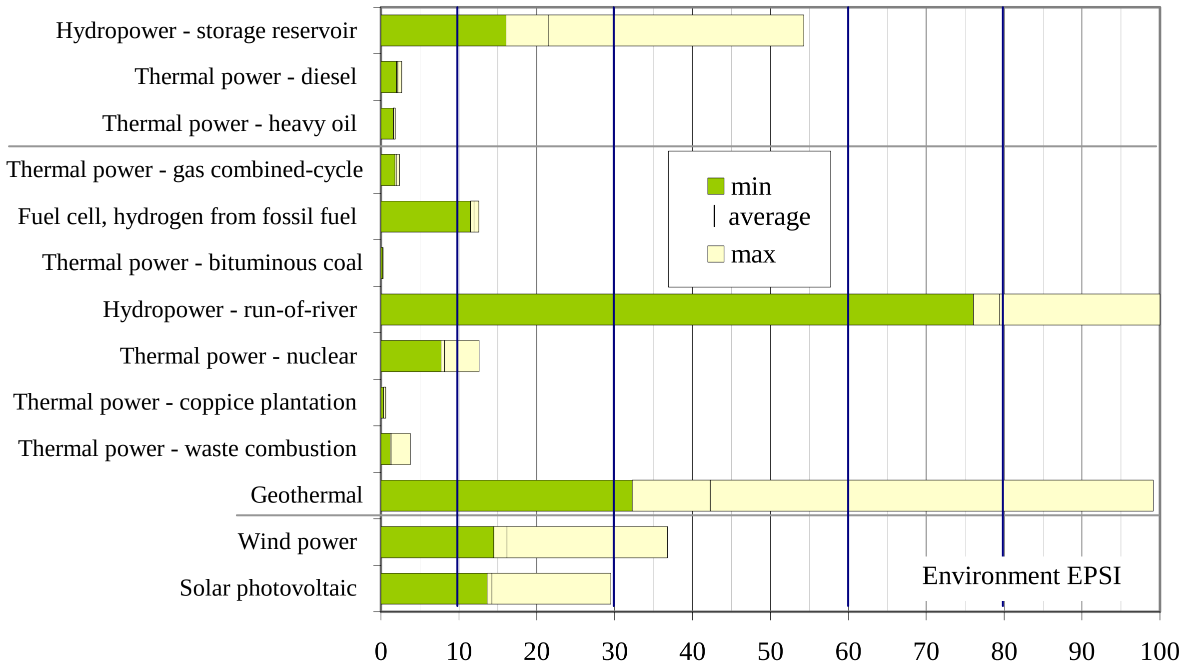

Fig. 2: Electricity Production Sustainability Index regarding the Environment criteria (EPSI env)

The figure 3 exposes the Sustainability Indexes regarding the Social Criteria (EPSI so) and we have the following comments:

- The most valuable systems, in a decreasing order are: geothermal, fuel cell with hydrogen from fossil fuel, wind power, thermal power diesel, hydropower run-of-river, and thermal power-coppice plantation. The high value of fuel cell is due to almost negligible risk aversion and low health impacts,
- Hydropower - storage reservoir has a mediocre or poor because of large resettlements occurred in some particular cases (this gives also the large range of the value) and risk aversion,
- Thermal power with fossil fuel or nuclear are mediocre.

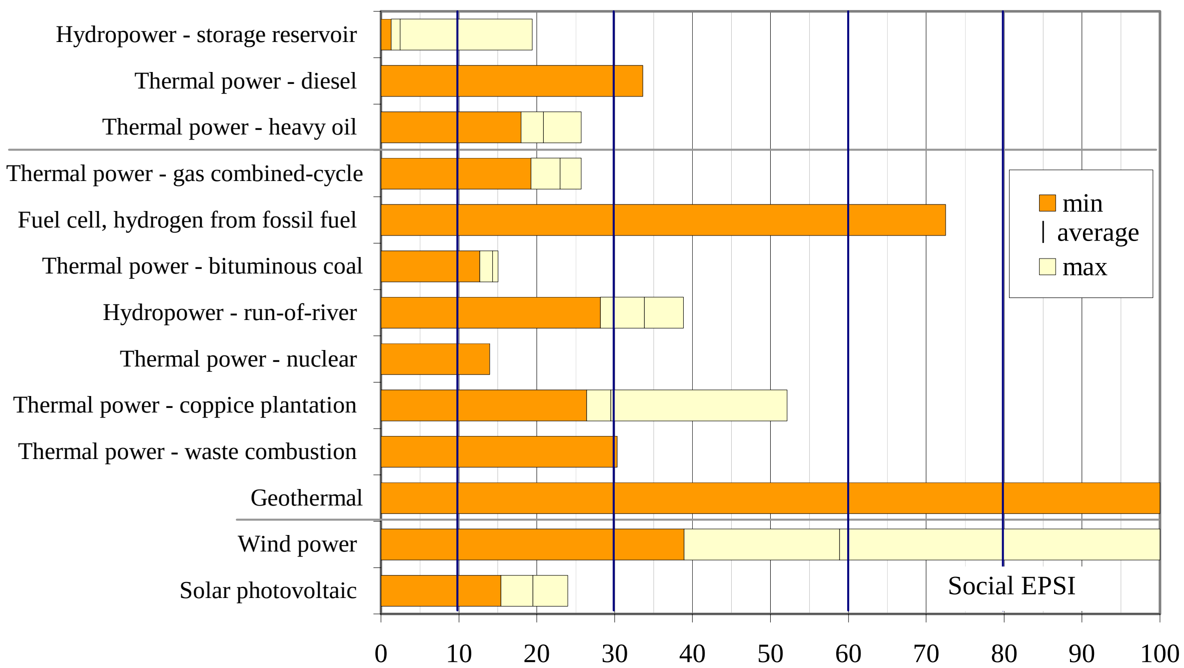

Fig. 3: Electricity Production Sustainability Index regarding the Social criteria (EPSI so)

On the figure 4 the Sustainability Indexes regarding the Economic Criteria (EPSI eco) is presented. We can say that

- Considering the mean values all the system have a good EPSI eco, at the exception of the solar photovoltaic,

- The best Indexes concern Hydropower with storage or run-of-river, Thermal power waste combustion, oil gas and coal.

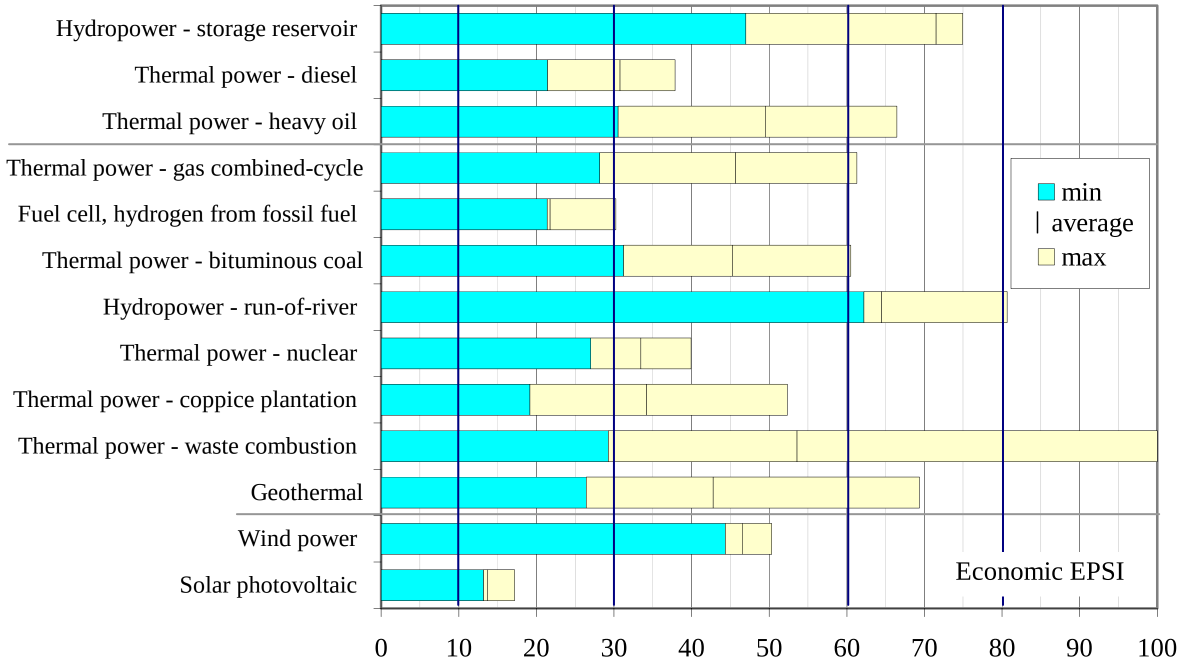

Fig. 4: Electricity Production Sustainability Index regarding the economic criteria (EPSI eco)

And now we can see on the figure 5 the sustainability Index regarding the Technical Criteria (EPSI tec). It appears that:

- Hydropower is very good or excellent (storage reservoir); all the thermal systems with combustion are good; nuclear is at the limit; wind power, solar, photovoltaic and fuel cell are mediocre.

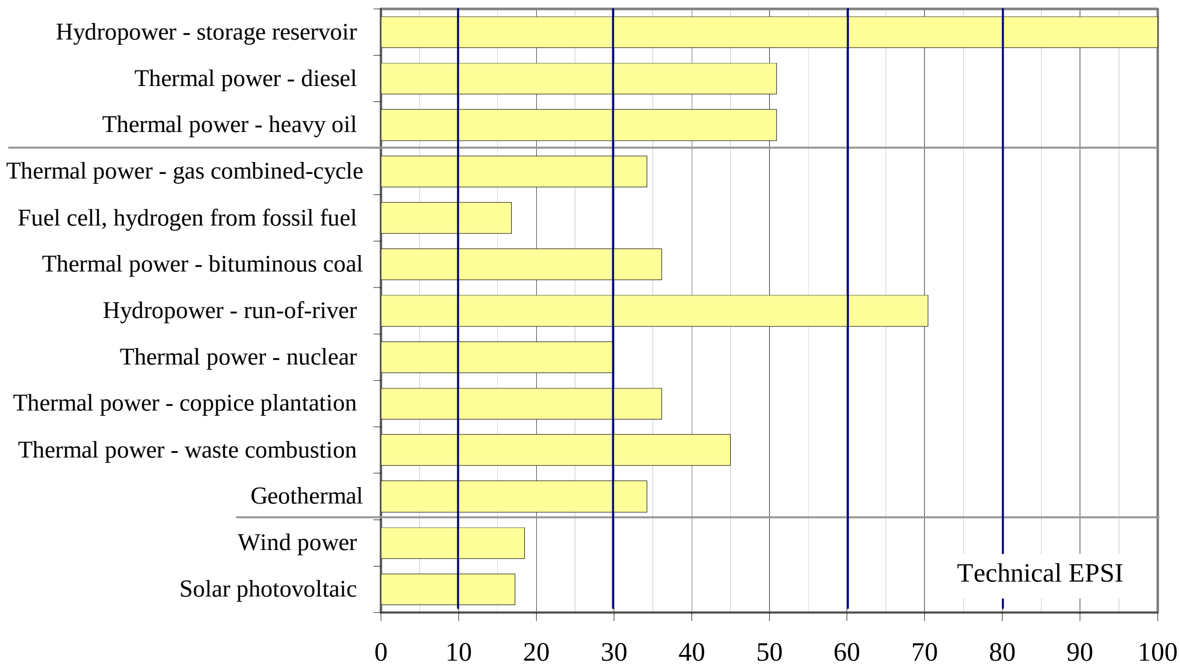

Fig. 5: Electricity Production Sustainability Index regarding the technical criteria (EPSI tec)

Finally the last Index represented on the figure 6 regards the Policy Criteria (EPSI pol). It is not surprising to see the high values of hydropower, wind power, geothermal, solar, and thermal with waste or coppice, all of them characterized by a good degree of independence and security of supply.

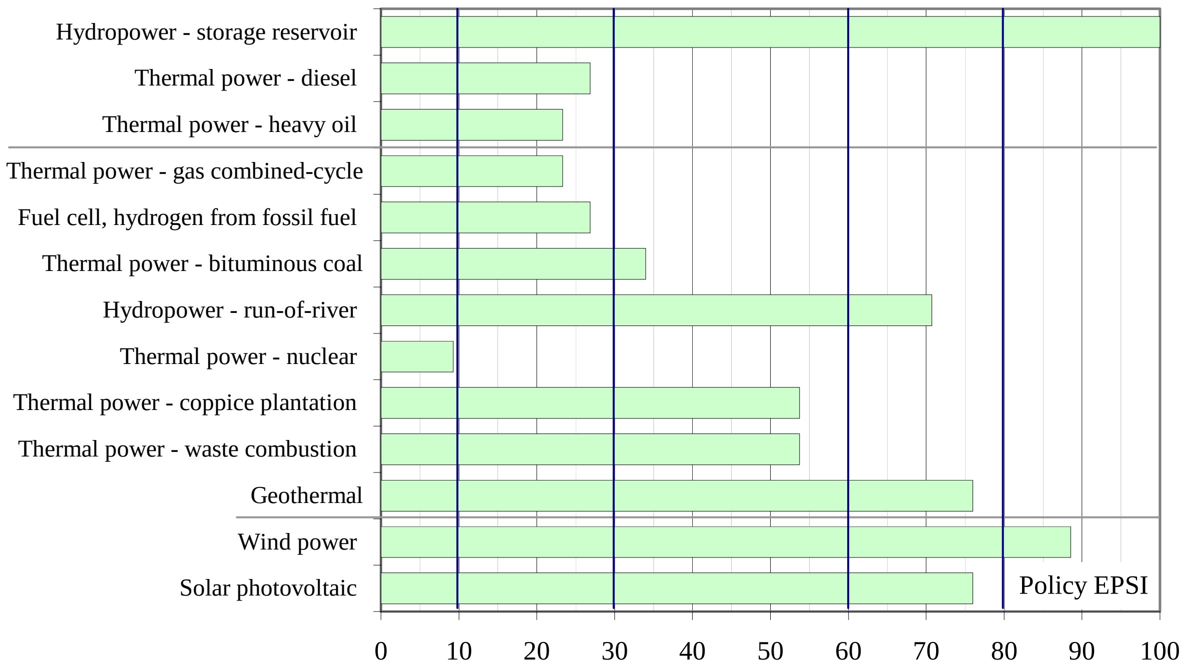

Fig. 6: Electricity Production Sustainability Index regarding the policy criteria (EPSI pol)

7. Values of global EPSI for the set of the 5 Criteria

An overall evaluation can be performed by the aggregation of the 5 Criteria. They should be weighted and for that it is necessary to define a policy: may we have for example to give advantage to Environment or to Economic Criteria. We propose to present three global scenarios: the first one with a larger weight on Economic and Technical Criteria, a second with a lager weight on Environment and Social Criteria and the last , "Neutral" with equal weights for the five Criteria.

Criteria subset	Economic-Technical	Environment-Social	Neutral
Environment	10%	50%	20%
Social	10%	20%	20%
Economic	50%	10%	20%
Technical	20%	10%	20%
Policy	10%	10%	20%
Total	100%	100%	100%

Table 3: Weight of the three scenarios: "Economic-Technical","Environment-Social" and "Neutral"

The 3 figures of the aggregated Criteria are presented hereby and we are giving the following comments, with reference to the sustainability scale of the Table 3:

- In the scenario of "Economic-Technical" policy, practically all the systems, with exception of Solar photovoltaic are good, with a special advantage to Hydropower and Geothermal. This result is not surprising in a world of free market where each production should be competitive.
- For the scenario of "Environment-Social" policy, all the thermal power systems appear poor and Fuel cell, Nuclear, Solar photovoltaic mediocre; only Hydropower and geothermal are good or very good.
- Finally, in the scenario of "Neutral" policy, none of the options are poor, the majority of Thermal and Nuclear system, Solar photovoltaic, Fuel cell are at the upper limit of the class mediocre or at the lower limit of the class good; only three systems dominate largely: Hydropower-run-of-river, Geothermal and Wind power.

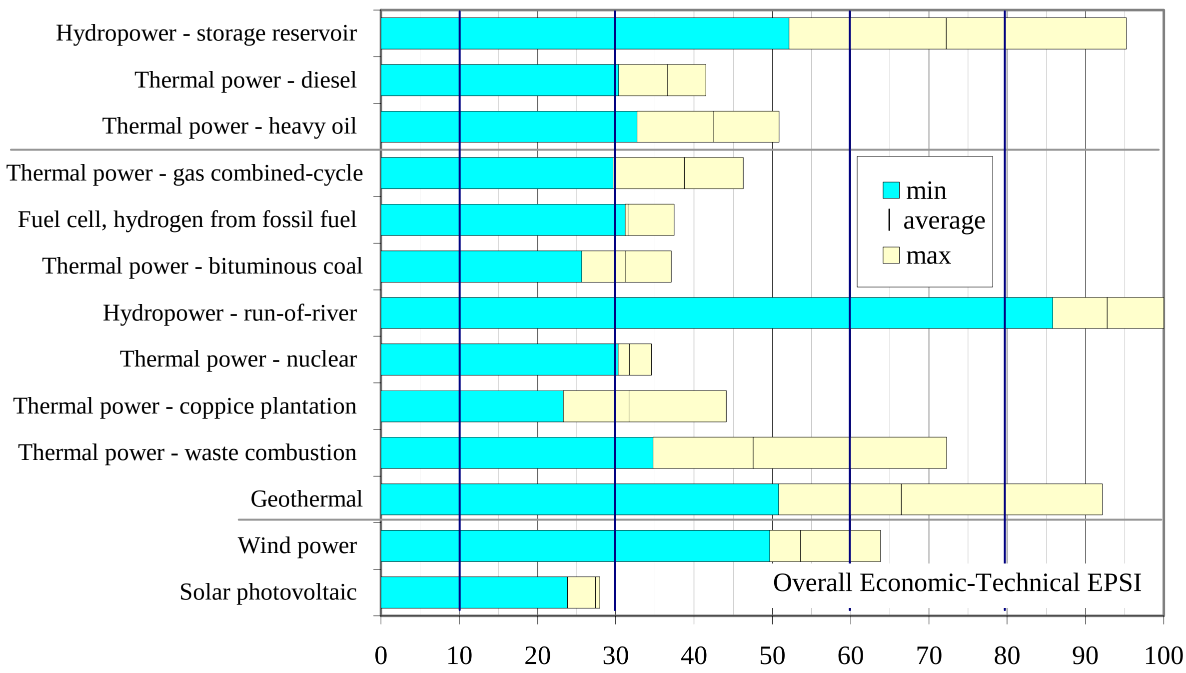

Fig. 7: Overall EPSI as regards to a predominantly Economic-Technical policy

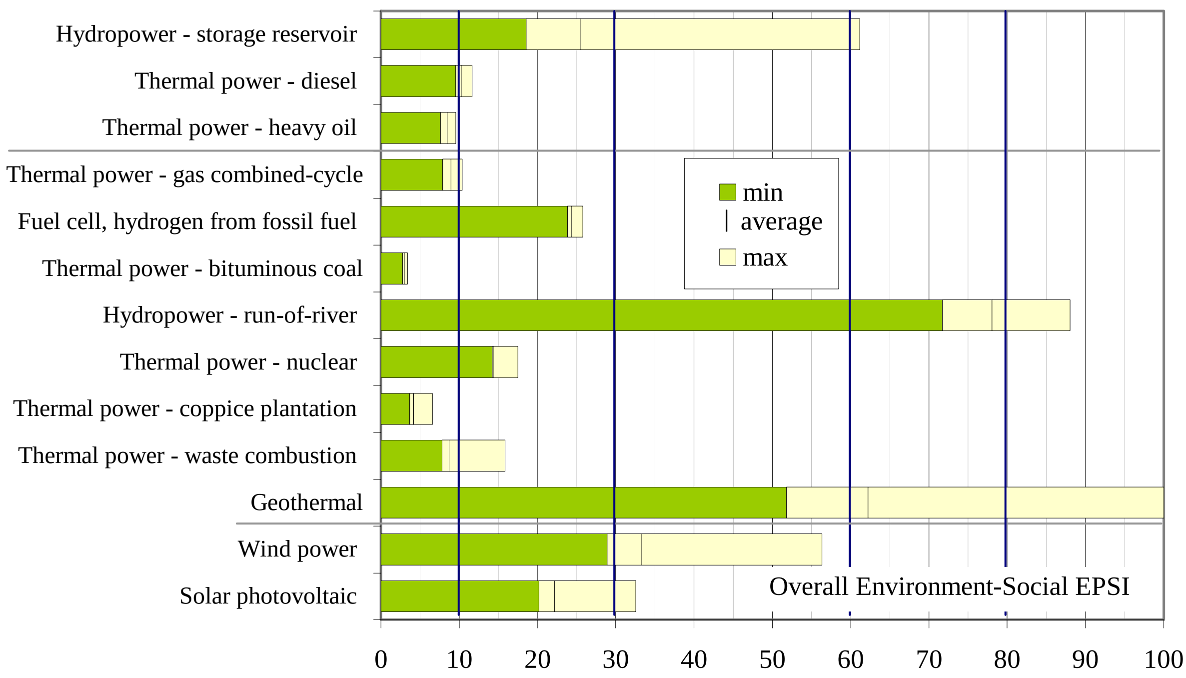

Fig. 8: Overall EPSI as regards to a predominantly Environment - Social policy

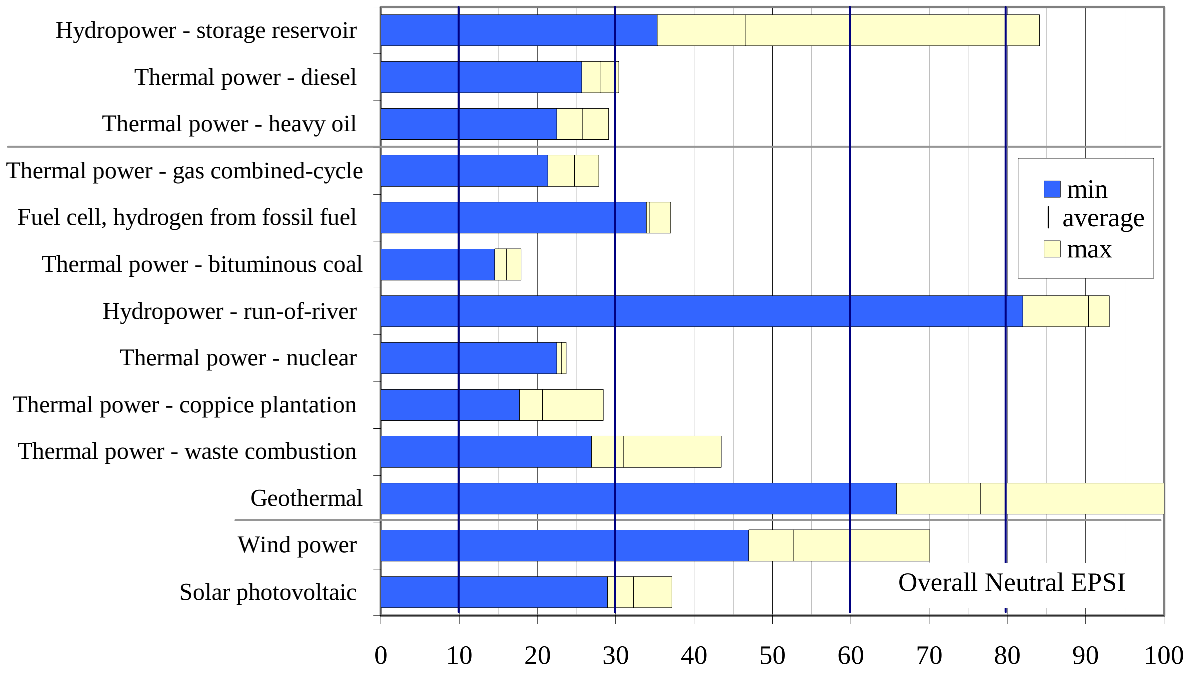

Fig. 9: Global EPSI as regards to a "Neutral" policy

8. Conclusion

We are not surprised by the result of this analysis of the sustainability of the various electricity generation systems, just perhaps by the good or very good position of Geothermal and Wind power. A confirmation is made of the high value of Hydropower.
The present considerations are a first approach, and a recommendation could be made to follow up in this way of identification and quantification of the Criteria and Indicators. The interest is not only the final result of the analysis, but the process itself with its various components: life cycle assessment of the generation systems, social and environmental impact, economic and technical assessments. This analysis allows a better understanding of the relativity of the problems, and could create a basis of fruitful and fair discussion between the persons concerned by in the development of energy resources, having in mind that the major objective is the poverty alleviation with a respect of the environment.

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