Comparison of the Fusion with Other Prospective Energy Sources

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1. Introduction

Since any power plant should be economically competitive to the other power sources, the plant economics is an important issue, but is just one of the requirements. The followings may be the major requirements to be posed for the future energy sources;

1. Abundant and widely available resources
2. Low emission of CO_2 as well as other undesirable substances and less waste to be disposed
3. Acceptable cost (cost of electricity and capital cost per kW) and flexibility in plant size (minimum size)
4. Stable power supply and less vulnerability to international affairs
5. Safety and security (bio-hazard potential and global security risks)

In the present study, we compare the following five possible energy options that may satisfy most of these requirements;

1) Terrestrial solar and wind power plants
2) Solar Power Satellites (SPS) on Geosynchronous Earth Orbit (GEO)
3) Advanced fission plants; fast breeder reactor (FBR) or light water reactor with Uranium from seawater (LWR-SW)
4) Fusion reactor
5) Advanced coal plant with CO_2 control

Is the fusion superior? (---or not?)
If the fusion is superior, how?

Method of assessment

Five main issues relevant to the five requirements are divided into sub-issues in order to clarify the various view points on each main issue.

A weight W of each sub-issue is assigned in order to assess the options.

The sum of W over each issue is 10.

Table 1 Issues and the weight

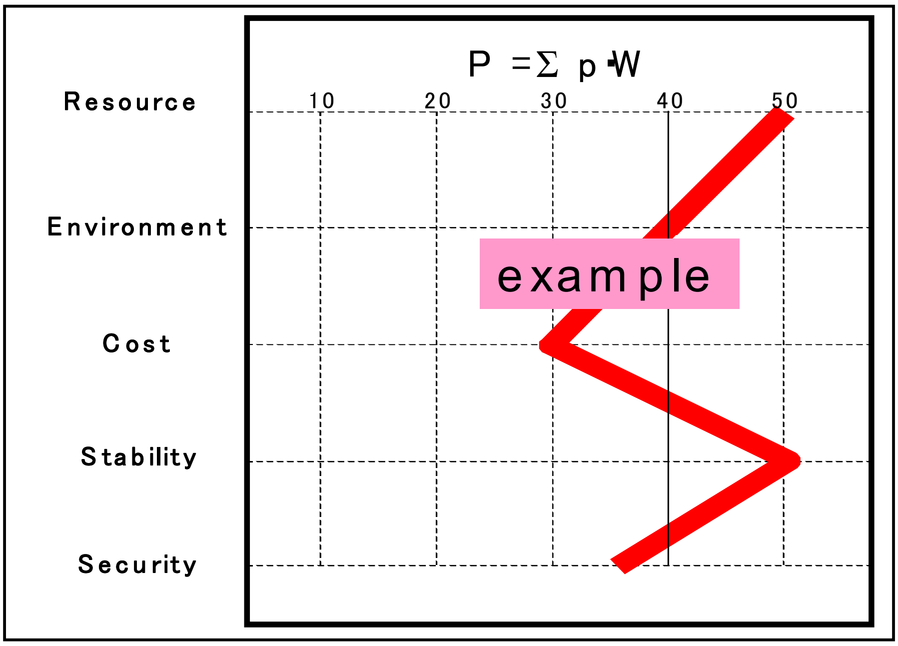
Main issues	Sub-issues	Weight
Resource	1) Restriction on resource	8
	2) Resource distribution	2
Environmental Issues	1) CO_2 emission	5
	2) Disposability of waste	5
Cost	1) Cost of Electricity (COE)	4
	2) Construction cost	4
	3) Flexibility in plant size	2
Stability of Power Supply	1) Stability of plant (restriction in principle)	8
	2) Vulnerability of operation (to international affairs)	2
Safety and Security	1) Hazard potential during operation	7
	2) Security against improper use or nuclear proliferation	3

Steps of assessment

1) Ranking each option on the main issue.
The best option is ranked as 1st, the next 2nd----
If one is very inferior, it should be ranked 5th
even when there is no option ranked as 4th.

2)The point p=5 for 1st rank, p=4 for 2nd----

3)The total point for a single main issue : $P = \Sigma\, p \cdot W$



NOTE!! The weight for each main issue is not determined here, because the purpose of this study is to show the features of each option for the requirements, e.g., merit and demerit.

Comparing the point of each option over a single main issue is meaningful, but the sum of points over all the main issues can not be a general yardstick, because the weight of main issues have not been defined here.

1. Resource

1) Restriction on resource [Zetta(10^{21}) Jouls: ZJ]

Power Plant	Reserve (tons)	Available energy (ZJ)	Rank
Solar wind	inexhaustible	inexhaustible, but limited by ~0.8 ZJ/year	1
SPS	inexhaustible	inexhaustible but limited by capacity on GEO (~0.006 ZJ/year)**	1
Fusion	D(seawater): 2.2×10^{13} Li(seawater): 2.4×10^{11}	5.1×10^{6}	1
fission	U (mine): 5.8×10^{6} U(seawater): 4.7×10^{9}	280 (FBR) 2600 (LWR-SW one through) 2.3×10^{5} (FBR)	1
Coal	9.8×10^{11}	26	5

** 180 satellites at intervals of 2 degree on GEO =180GWe.

1)Solar/wind and SPS are inexhaustible. 1st

2)Since the reserves of resource and available energies from Fusion and Advanced fission is practically unlimited. 1st

3)Note that, if the Uranium from seawater is used, the available energy attains 2600 ZJ even with one-through fuel strategy.

2) Resource distribution

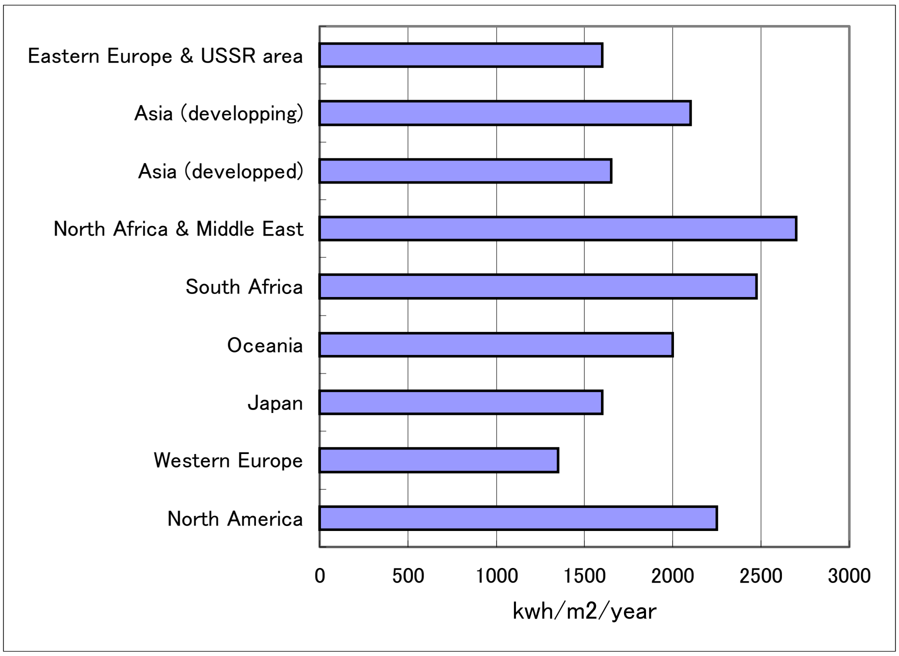
Power Plant	Resource availability	Rank
Fission:	U: from seawater Pu: self-breeding	1
Fusion	D & Li: from seawater T: self-breeding	1
Solar wind	depend on country (See Fig 1)	2
SPS	restriction in siting due to the large space for rectena (see Fig 2)	2
Coal	82% of world resource is in China, USA and former USSR area	3

1) The fuels for fission and fusion are available from seawater, or by self-breeding. 1st

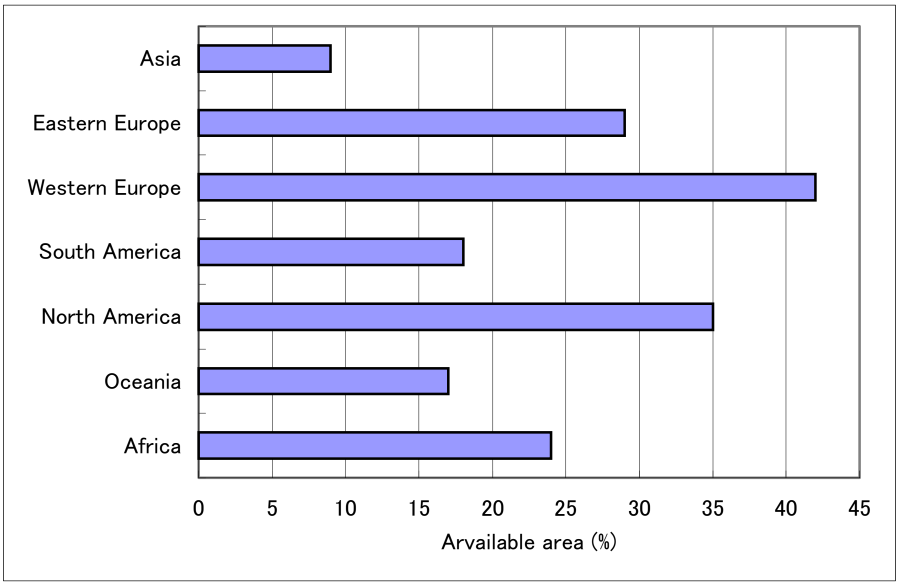
2) The available energy from solar power and the available area for wind power depend on the country. The rectena (a power receiver) of SPS is huge and may become a critical constraint in siting. 2nd

3) Since the resource distribution of coal is localized (82% of world resource is in China, USA and former USSR area). 3rd

Fig. 1
Resource distribution of solar and wind power

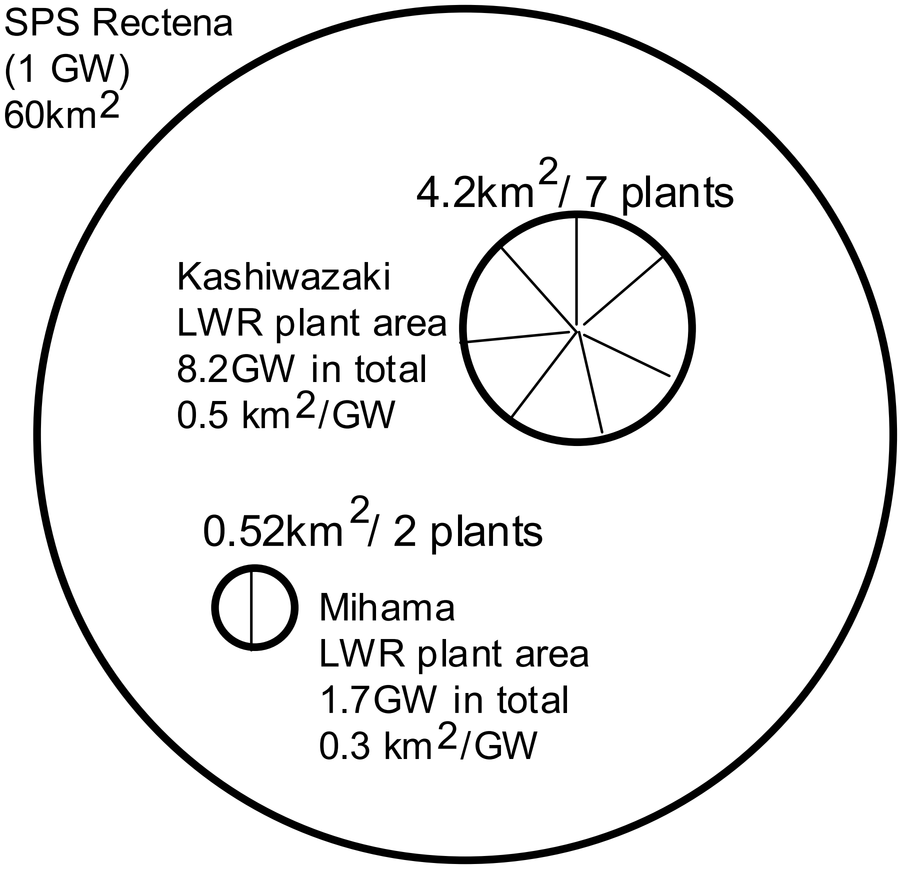


a)Average power density of sunshine



b)Area available for wind power plant

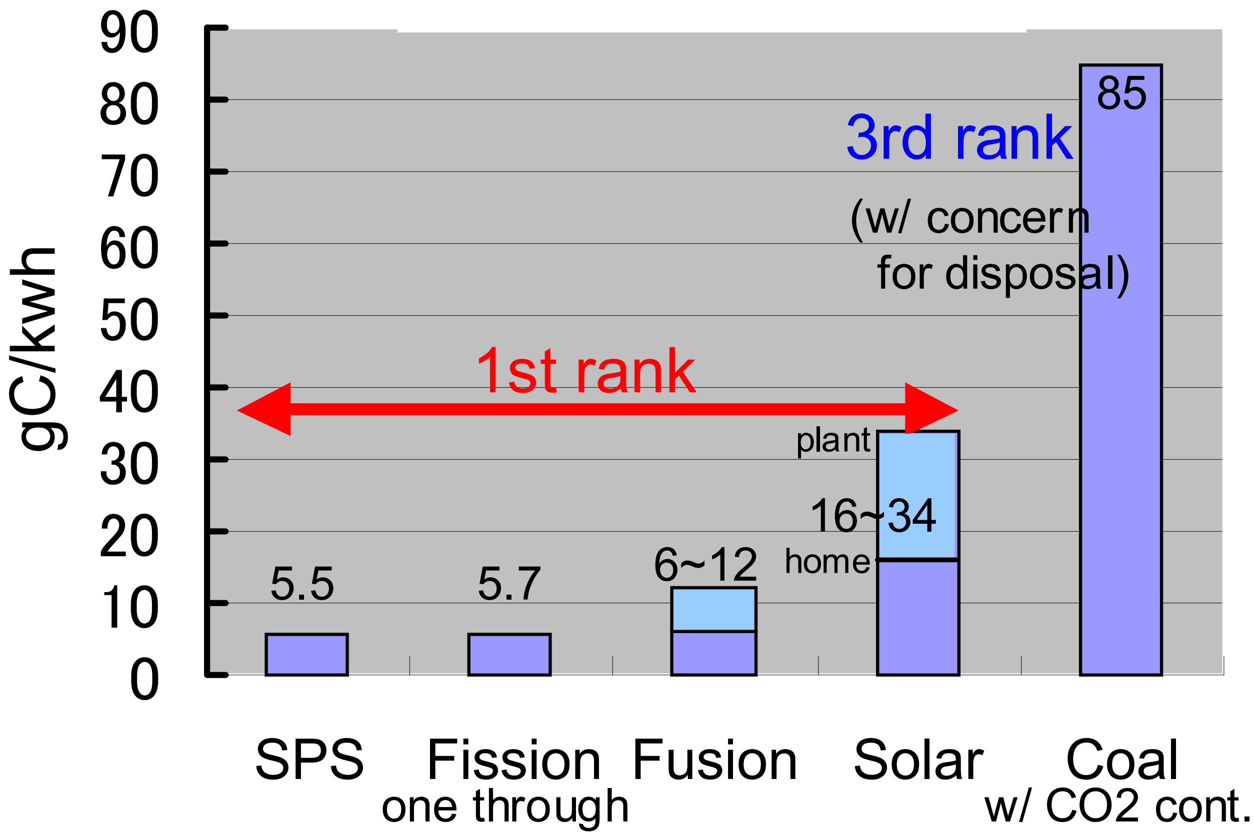
Fig.2 Comparison of plant area on the earth.



Note that the safety zone is excluded for the SPS rectena while the areas for LWR include it. Also note that the area of ITER (not commercial plant and not shown here) is 0.4 km^2.

2. Environmental Issue

1) CO_2 emission



1) **The low emission group (SPS, Fission, Fusion, and Solar/Wind) should be ranked as 1st.**

2) **The coal is ranked as 3rd, because the emission from coal plant is higher than the above low emission group and besides, there is some concern for disposal of sequestered CO_2 .**

The other undesirable substances will be minor, except for the coal plant.

2) Disposability of waste *(except CO_2)*

Power Plant	Description	Rank
Solar wind	easily disposable and recycled, no radioactivity	1
SPS	$2x10^4$ tons on GEO* is difficult to dispose, possibly no radioactivity	2
Coal	huge ($2x10^7$ tons from 1 GW plant), very low radioactivity	3
Fusion	large ($2x10^4$ tons) and radio- active waste, but neither high level nor long life	3
fission	high level and long life radioactive waste is difficult to dispose	5

1) Concerning the disposability of waste, the Solar/Wind power plant is no doubt the best. 1st

2) On SPS, there is a concern on how to dispose a satellite (20,000 tons) on GEO. 2nd

3) The ash from coal is huge. The waste from fusion is 20,000 tons throughout the plant life and it is radioactive, but neither high level nor long life. 3rd.

4) Since high level and long life radioactive waste from the fission plant is difficult to dispose, the fission plant is ranked as 5th.

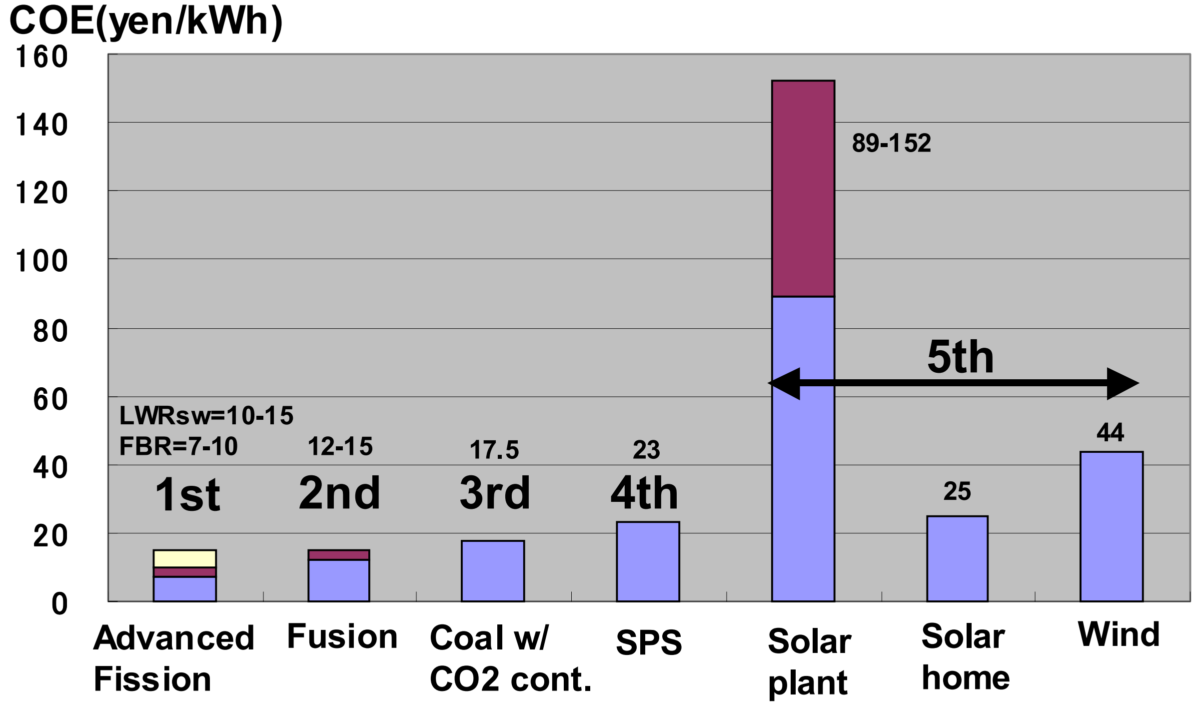
3. Cost

It should be noted that any issue can be reflected to the cost.

For example, disposal cost of radioactive waste should be included in the cost of fission plant.

Therefore the costs considered here may include all the costs to achieve the features assumed in the other main issues.

1) Cost of Electricity (COE)



1) The ambiguity in the COE for LWR-SW depends on the Uranium cost from seawater.

2) The cost of Fusion reactors has been widely discussed and there is large ambiguity. We have adopted here the cost based on advanced tokamak reactors, such as ASSTR-2 (by JAERI) and CREST (by CRIEPI).

3) The cost of SPS is based on the value given in a report by NEDO*.

*:New Energy and Industrial Technology Development Organization

2)Unit Construction cost

Power Plant	**Unit cost of construction for 1GWe plant (10^4 Yen /kW)**	**Rank**
Coal with CO_2 control	28	1
Advanced fission	32 a value of 1GW LWR is used here	2
Fusion	40~50	3
Solar or wind	Solar: 80~130, ~31 Wind: 50	3
SPS	240	5

1)The order of ranking is;
Coal 1st, Fission 2nd, Fusion and Solar/Wind 3rd
2) The construction cost of SPS is very expensive.5th

3) Flexibility in plant size

Minimum scale of plant to be achieved without significant COE increment is shown in this table.

Power Plant	Minimum scale of plant	Rank
Solar or wind	flexible (no scale merit)	1
Coal with CO_2 control	~200 MW (no inherent limit)	2
Advanced fission: FBR,LWR-SW	~300 MW (no inherent limit)	3
Solar Power Satellite	~500 MW (no inherent limit)	4
Fusion	~1000 MW	5

1) The Solar/Wind is the 5th in COE, but the 1st in Flexibility in plant size. This means that the issues on cost must be discussed from various view points.

2) Although there is no inherent limit for plant size for SPS, a strong constraint exists, because the size of rectena seems to be determined by the beam divergence rather than the transmission power. 2nd

3) The minimum size of fusion reactor will be restricted by the inherent feature of fusion reaction. 5th

4. Stability of Power Supply

This main issue includes two sub issues;

1) The inherent operational restriction,
"stability of plant".

2) A new concept on the plant stability,
"vulnerability" of operation to international affairs, where we have noticed that the plant output can be interrupted if supply of fuel or resource is disturbed.

Stability of Power Supply

1) Stability of plant (restriction in principle)

Power Plant	Operational characteristics	Rank
Coal with CO_2 control	stable	1
Fission:	stable	1
Fusion	stable	1
SPS	stable but short discontinuations due to eclipse by the earth	1
Solar or wind	unstable	5

1) The coal, fission and fusion plants can be operated continuously. There is no limit, at least, in principle. 1st

2) The SPS is also ranked 1st here, but note that the output is to be interrupted due to eclipse by the earth before and after the autumnal equinox and the spring equinox (less than one hour per day). 1st

3) The solar/wind power plant is inherently unstable. The cost to overcome this unstable feature, which is excluded in our cost assessment, will be very expensive. 5th

Stability of Power Supply

2) Vulnerability of operation (to international affairs)

Vulnerability to human evil and malice (like terrorism) toward the plant is out of present consideration.

Power Plant	Description	Rank
Solar or wind	invulnerable	1
SPS	invulnerable	1
Fusion	invulnerable	1
Fission	less vulnerable, but if international transports are required for the fuel cycle, there is some vulnerability.	2
Coal	vulnerable to international affair, if imported fuel is used	3

1) The solar/wind power plant and SPS is highly invulnerable to international affairs. 1st

2) The fusion is also ranked as the 1st, because fusion fuel can be obtained from seawater and the fuel cycle can be closed in a single plant. 1st

3) The fission plant is less vulnerable too, but if international transports are required for the fuel cycle, there is some vulnerability. 2nd

4) The fuel availability of coal plant is possibly more vulnerable than the other options. 3rd

5. Safety and Security

Since operational safety must be guaranteed for any commercial plants, it is a compulsory requirement.

Therefore only the issues related to security should be compared here.

When we consider the security of plants, we assume here also peaceful world situation. Any plants can be dangerous under the human malice such as war or terrorism.

The first sub issue for security is a ranking by the hazard potential in the plant during operation.

1) Hazard potential during operation

Power Plant	Relative value of hazard potential	Rank
Solar or wind	regarded as 0	1
SPS	regarded as 0 unknown effect by electro-magnetic wave is conceivable, but was excluded here	1
Coal with CO_2 control	regarded as a low value similar to chemical plants	2
Fusion	~1/1000 (radioactive)	3
Fission	1 (radioactive)	4

1) The solar/wind and SPS has been regarded as having no hazard potential. 1st
There might be some unfavorable effect by electro-magnetic wave near the SPS rectena. (23mW/cm^2).
It was neglected from the present consideration.

2) The hazard potential of coal plant is regarded as a low value, i.e., similar to those of many chemical plants. 2nd

3) The fusion and fission plants have a high hazard potential. But the bio-hazard potential of fusion is lower by about 1/1000 than the fission plant.
Fusion: 3rd Fission: 4th

2) Security against improper use

This is related to the security against improper use of plant, where 'improper' may mean unauthorized or internationally unaccepted, e.g., use by terrorists or use for proliferation of nuclear explosive devices.

Power Plant	Description	Rank
Solar or wind	no insecurity	1
Coal with CO_2 control	no insecurity	1
Fusion	no merit for military use	1
SPS	1GW beam emitter from space might be difficult to be accepted by neighbors	2
Fission	security problem due to Pu and U_{235} is essentially unavoidable	5

1) From this view point, no insecurity is found for the solar/wind plant and coal plant. 1st
No noteworthy merit is found for using the 'commercial' fusion reactor for such purposes. 1st

2) The SPS, which can be regarded as an 1 GW power beam emitter from the space, might be difficult to be accepted by neighboring countries. 2nd

3) The fission plant is very inferior from a view point of nuclear proliferation. 5th

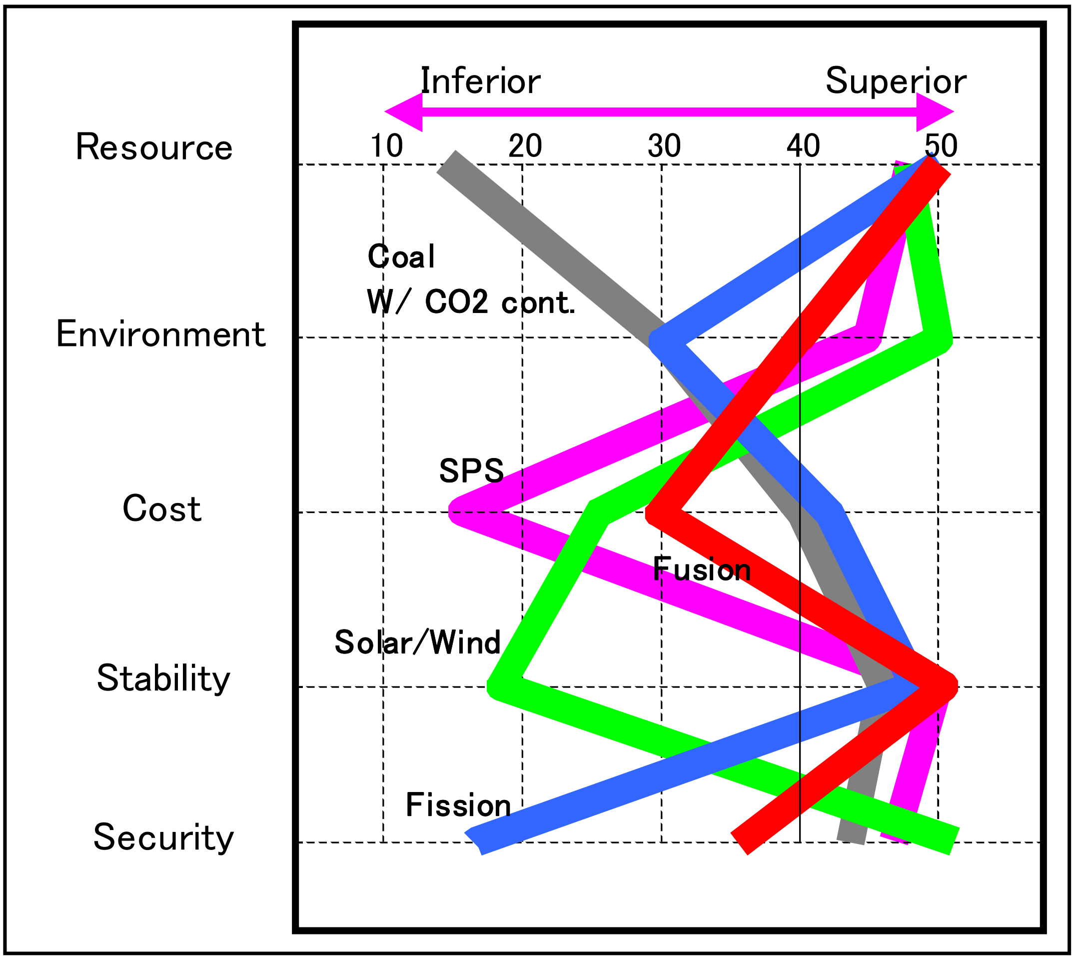


Fig.3

Summary of point distribution

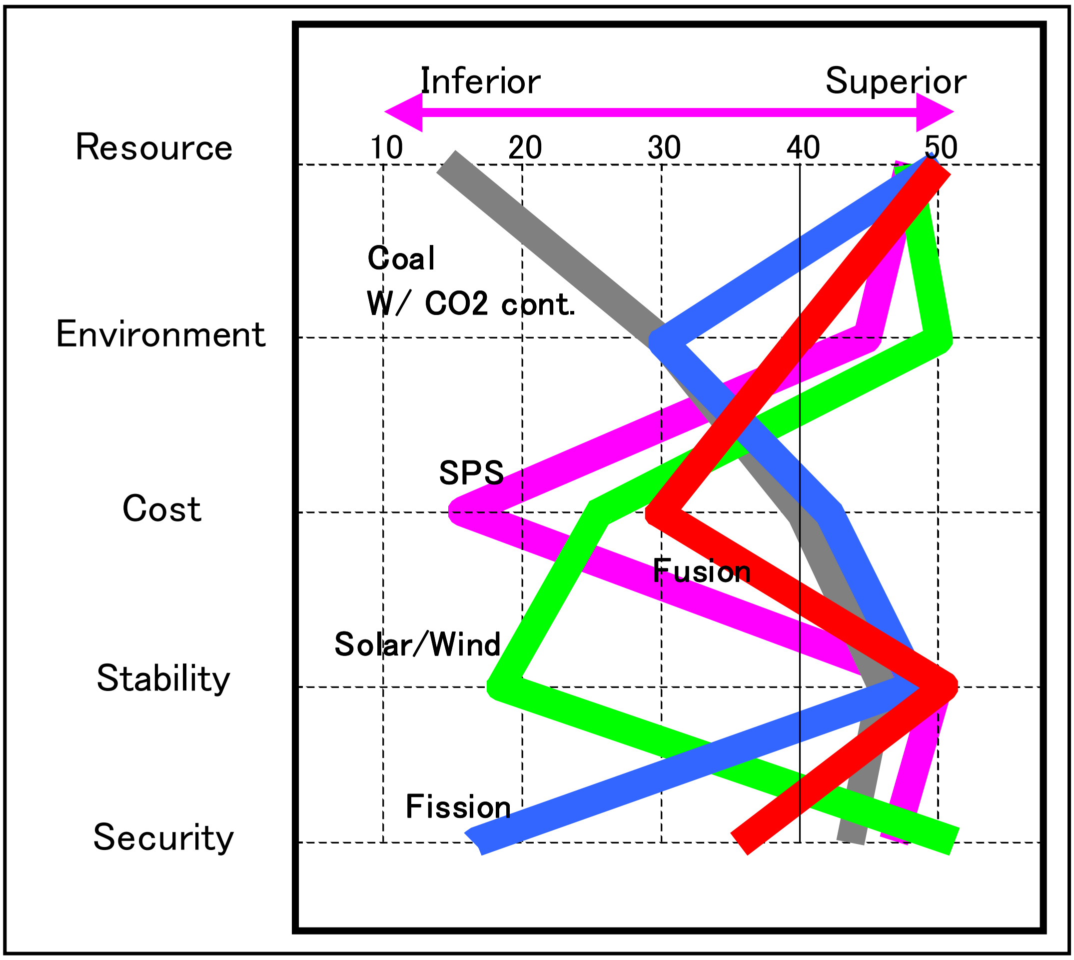
This figure of P =Σ p·W clearly shows the features of each option. Each option has drawback(s).

1) The major drawback of coal is in Resource.

2) The serious drawback of SPS is Cost.

3) It is Stability for solar/wind.

4) The points of advanced fission plants are high enough except for Security, and they appear to be a reliable energy source for a long time. But difficulties associated with security may be unavoidable.



5) The points of fusion are also high enough.
The drawback of fusion is Cost, but it is still ranked as 3rd for Cost. This means that the fusion plant has no serious drawback.
The fusion gets the 1st for Resource and Stability, but it is not a sole winner. This fact tends to make the merit of fusion somewhat ambiguous.
The superiority of fusion is due to the fact that there is no serious drawback (i.e. no 5th rank).

When we discuss the future energy options, we should consider what is the serious drawback as well as what is the merit.

Conclusion

1) Rank and point for the requirements as future energy sources are assessed for the five options selected.

2) Every option has drawback(s) as well as merits. When we discuss the future energy options, we should consider what is the serious drawback as well as what is the merit.

3) The results of the study show that fusion reactor does not mark a higher average point than other options, but looks superior as a whole, meeting every requirement reasonably well without serious drawbacks for any of them.

4) Since a drawback of fusion is the issues relevant to cost, a quest for a smaller plant size with lower cost may be the most important issue to maximize the attractiveness of fusion power plants.

5) It is noteworthy that the issue for fusion is largely scientific and technical, i.e., it might be overcome by further efforts.