Energy Payback Time of Grid Connected PV Systems: comparison between tracking and fixed systems.

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Abstract

A review of existing studies about LCA of PV systems has been carried out. The data from this review have been completed with our own figures in order to calculate the Energy Payback Time of double and horizontal axis tracking and fixed systems. The results of this metric span from 2 to 5 years for the latitude and global irradiation ranges of the geographical area comprised between $-10°$ to $10°$ of longitude, and $30°$ to $45°$ of latitude. With the caution due to the uncertainty of the sources of information, these results mean that a GCPVS is able to produce back the energy required for its existence from 6 to 15 times during a life cycle of 30 years.

When comparing tracking and fixed systems, the great importance of the PV generator makes advisable to dedicate more energy to some components of the system in order to increase the productivity and to obtain a higher performance of the component with the highest energy requirement. Both double axis and horizontal axis trackers follow this way, requiring more energy in metallic structure, foundations and wiring, but this higher contribution is widely compensated by the improved productivity of the system.

Keywords: Grid-connected PV systems; Life Cycle Assesment; Energy Payback Time; PV Tracking systems.

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I. INTRODUCTION

During its life cycle, besides producing useful energy, heat and waste, a generator system requires the income of energy and materials for the manufacturing of their components, the transport, installation and start-up of the equipment, and the replacement of those element which finish their life cycle. The Life Cycle Assessment (LCA) documents and analyzes the different impacts over the environment due to the existence of the system, from the manufacturing to the dismantlement and recycling ("from cradle to grave" is an eloquent expression for this concept).

Three data sources are to be used when studying the energetical LCA of a Grid Connected PV System (GCPVS):

- The Life Cycle Inventories (LCIs) of the different processes involved in a GCPVS. From these LCIs it is possible to estimate the energetical impact of the system[1].
- The global irradiation of the location where the GCPVS is to be installed.
- The technical characteristics of the set of components of the GCPVS in order to estimate the energy to be produced during its life cycle.

The figure 1 summarizes this approach applied to a GCPVS. The output energy can be estimated with the global radiation and some characteristics of the main components of the system. In this paper we analyze the energetical impact of the main components of a GCPVS in order to obtain information about the flow of energy required for the system functioning. This analysis is to be applied to fixed and tracking systems, which will be compared from this LCA approach.

It must be remarked the existence of several publications which have analyzed the environmental impact of PV systems using different approaches. In general, two main groups can be differentiated: first, those which give emphasis to the photovoltaic module paying less attention to the balance of the system (BOS);

[1] It shall be paid attention to the fact that the LCI compiles figures of *primary* energy.

second, those which study in detail the impact of the BOS and use the results of the first group for quantifying the impact of the module. For the first group it is remarkable the contribution of E. Alsema [Als00] and the European supported project Crystal Clear [DWSA05], although some other authors have also contributed with a variety of results [KL97, KJ01, Jun05, DF98]. In the second group, the analysis of [MFHK06] is an important reference, although other not so recent contributions include interesting comparatives between PV systems and other techniques of electrical generation [MK02, KR04, FMGT98]. However it is noteworthy that none of these references includes tracking systems in their analysis, and this is one of the main contributions of our investigation.

II. METHODS

A. Definition of the frontier

The application of an energetical LCA to a system requires the definition of spatial and temporal borders containing the components and processes which are to be taken into account in the analysis. Moreover, this definition of frontiers allows to establish useful indicators for comparison with alternative typologies or technologies. In our framework, the objective is to analyze the behavior of some techniques of solar tracking along their life cycle. Therefore, the LCA will leave out those components and processes which depend from local conditions (for example, a local normative for Medium Voltage (MV) installations), and which should be chosen by the engineer whatever the tracking technique adopted. In order to summarize with a label, our frontier is the Low Voltage (LV). Hence, our LCI includes the energy used for the manufacturing and transport of the PV modules, LV wiring, inverters, support structure and foundations. This LCI will not include the impact of MV centres, protections and lines. Other components which are included inside the LV frontier are discarded due to their low impact in the global sum: LV electrical protections, manpower, communication systems, and documentation tasks.

During the life cycle of a GCPVS (30 years in this study) some components shall be substituted in order to guarantee the availability of the system as an electrical generator. The energetic impact due to this replacement should be included in the analysis. The failure rate of a PV module is very low –frequently, manufacturers guarantees their products for 20 years–, and consequently the energetic impact is negligible. The inverters have higher failure rates, but mostly due to their electronic components. The commutation bridge and mainly the transformer –the most important parts of the inverter in the energetic impact– have low failure rates. Moreover, it is now possible to find inverters designed to allow for the substitution of the control cards without replacing the whole equipment. Therefore, the energetic impact of the inverters maintenance will be modelled as a replacement of the 10% of the inverter parts every 10 years [MFHK06]. In a 30 years life cycle this assumption increases around 30% the energetic impact of the inverter. Wiring, support structure and foundations are characterized by their stability: to guarantee their correct functioning only requires minor actuation without influence in the energetic calculations.

B. Calculation of required energy

Now that the frontier which delimitate the analysis is defined, the not so evident task of assigning unitary energy values to every process and product starts. As stated in the introduction, there is a variety of documents which report set of values for PV systems. This bibliography provides detailed information about the main component, the PV module, although paying less attention to the impact of other components of the GCPVS —those subsumed by the somewhat deprecative label of Balance of System, BOS—. It will be shown in the discussion of results that the contribution of this BOS means around the 25% of the total input of energy, value not to be depreciated.

It is worth remembering that the variety of materials and technological procedures are not easily quantified with precision and generality; moreover, the difficulties due to industrial privacy add noise to the information. For example, [Als00] carries out a revision of documented estimations, and finds a wide range of values comprised between 5 300 y 16 500 MJ/m² for the manufacturing of monocrystalline modules. Furthermore, even though a comparative analysis is carried out for a better estimation, the uncertainty is not lower than 40%. Accordingly, the results we are to obtain are merely indicative and only useful in the context of the aforementioned comparative.

In order to construct the global result for the system, we have studied projects designed and installed by Isofoton in Spain concerning double axis tracking, horizontal North-South tracking and fixed systems (Table I).

1. PV module

For calculating the energy required by a PV module, we will follow the reference [DWSA05]. This document is the result of a collaborative project, where several private companies and investigation institutions have worked together for compiling LCIs representing the state of the art of the technology of manufacturing crystalline silicon PV modules. According to this project, the primary energy devoted to the manufacturing of PV monocrystalline framed modules is 5 200 MJ/m^2. It must be remarked that the energy required for the aluminum frame has been estimated from [BAH97] according to the proportion of recycled aluminum used in the process of Isofoton. This modificaction results in a slightly lower estimation for the energy required by the PV module, 4954 MJ/m^2 (Table II)[2].

[2] It is worth pointing that reduction of the energy required by PV modules can be obtained by several strategies: reducing the thickness of the solar cell; increasing the efficiency of PV cells; recycling wasted cells for their subsequent reuse [GLWR05]; concentrating the light and thus reducing the active material thanks to the use of optical components. On the pro side of this last strategy, the cells included in these systems usually offer efficiency figures better than those of the conventional modules, with the consequent reduction in active material. On the con side, these modules are blind to diffuse radiation and demand a tracker system with high structural and precision requirements. Therefore, the most important energy consumer in this kind of systems is now the steel of the support structure, with more than the 40% of the total [PD05].

2. Inverter

The energy required by the manufacturing of inverters has been calculated from the Table I of [MFHK06]. This table provides a material inventory of a 150 kW inverter. The embodied energy of the inverters included in the projects of our Table I has been calculated from this inventory assuming that the requirement of materials of a central inverter is similar for different manufacturers and proportional to the total weight of the inverter. The set of inverters employed in these projects have been manufactured by the Spanish company Ingeteam.

The inverters of 25 kW power are installed inside the double-axis tracker column and therefore no additional housing is required for their protection. However, larger inverters are installed inside a building. A typical inverter building (10 meters width, 4 meters length, 3 meters height) allows 6·100 kW inverters inside with an estimated embodied energy of 162 174 MJ.

The result of these calculations is summarised in the Table III. The estimated embodied energy includes the replacement of 10% of the equipment once every 10 years. The average inverter includes the embodied energy in the building for the 80 kW and 100 kW inverters.

3. Fixed and tracking structures

Two different double-axis tracker have been installed in this set of projects: Isotrack25 and Ades6f22m. The energetical requirement assumed for the double-axis GCPVS is the average of the energy embodied in both trackers.

The support structure for the PV generator of the Isotrack25 is a grid of steel (23,9 m. width and 9,6 m. length). The total weight of this steel structure (including the cylindrical axis) is 7 150 kg. Its column is a concrete tubular structure (5 m. height and 1,5 m. diameter). This column fits with a square base (6 m. width, 6 m. length and 0,8 m height). The tracking mechanisms (one electrical motor for each movement and a ring for the azimuthal movement) of the Isotrack25 are integrated in a steel element which is coupled to the elevation axis and to the steel grid. The yearly energy consumption of these mechanisms is around 13 kWh/kWp.

The grid for the PV generator of the Ades6f22m is an steel structure (23 m. width and 10,5 m. length), which is coupled to a column through two arms. The column is a steel hollow structure (1,8 m. height and 1,4 m. diameter). This column fits with a square base (6 m. width, 6 m. length and 0,5 m height). The total weight of the steel structure (including the grid, arms and column) is 7 500 kg. The tracking mechanisms (two electrical motors and a ring) for the azimuthal movement are integrated inside the column, while the two linear hydraulic motors for the elevation movement couple the arms with the generator grid. The yearly energy consumption of these mechanisms is around 7 kWh/kWp.

For the horizontal North-South tracking system, the design included a tracker manufactured by the Spanish company Jupasa. A version of this tracker was installed in the PV Toledo plant. This tracker is 2,7 m. height, 4,8 m. width, and 12,9 m. length. The total weight of the metallic structure is 10 465 kg. It needs 10 foundations, 2 of them located at the extremes (2,8 m^3 each), 1 at the centre (3,6 m^3) and 6 at intermediate points (2,6 m^3 each). The tracking mechanism is an electrical motor with a transmission chain fixed to the generator grid. The yearly energy consumption of this mechanism is around 4 kWh/kWp.

The fixed systems use a steel structure with a weight of 128,13 kg/kWp and concrete foundations (without steel) of 1 m^3/kWp.

This information is summarised in Table IV.

4. Wiring

The unitary energy values corresponding to the manufacturing of wire (copper an aluminum), support structures (galvanized steel) and foundations (steel and concrete) have been calculated from [BAH97]. The volume of wiring materials depends on the ground cover ratio (and therefore on the tracking mode of the GCPVS). However, other conditions such as local technical regulations greatly affect the relation between requirement of terrain and volume of wiring. As an approximation, the energy requirement for wiring in this analysis is the average of the requirements of GCPVS #1 and #2 of Table I for fixed systems, the average of the requirement of the GCPVS #3 and #4 for double-axis tracking systems, and the requirement of GCPVS #5 for horizontal N-S axis tracking systems.

5. *Transport*

The energy devoted to the transport of equipment and materials has been calculated from figures published at [Wik08]. The energy required for transporting the main components has been estimated suppossing that the GCPVS is at a distance of 850 km from the support structure manufacturer, 500 km from the inverters and modules manufacturers, and 100 km from the foundations and wiring suppliers.

C. The energetic mix

The production process of a PV module is mainly electrical (the 80% of the input primary energy). Therefore, the primary energy quantities depend strongly on the conversion efficiency of the energetic systems which feed the different stages of the whole process. The efficiency values are calculated from the composition of energy sources —the energetic mix—, which is variable between countries and regions. In this document a value of 0,31 has been used as representative of the energetic mix of the UCTE[3] region.

D. Energy Payback Time

In order to compare different energy generation technologies, several metrics can be calculated from required energy (E_{LCA}) and produced energy (E_{ac}) during the life cycle. The metrics commonly used are *efficiency of life cycle* and *energy payback time* [Mei02, KL97].

When analyzing solar and wind energy systems, where the solar and wind

[3] The "Union for the Co-ordination of Transmission of Electricity" (UCTE) is the association of transmission system operators in continental Europe, whose objective is to coordinate the interests of operators belonging to 23 European countries.

resources does not imply any energetic cost, the results provided by the efficiency of life cycle are nonmeaningful. In this context, the Energy PayBack Time (EPBT) is more useful and hence its higher frequency of use in the bibliography previously reviewed. This document will only consider this metric for the comparisons. The EPBT is calculated with:

$$EPBT = \frac{E_{LCA}}{E_{ac}^{y}} \tag{1}$$

where E_{ac}^{y} stands for the energy produced by the GCPVS during one year. It must be stressed that, since LCIs values are primary energy, the energy produced by the PV system (E_{ac}) is also translated to primary values before the metrics are calculated.

E. Calculation of the energy produced by the PV system

The energy produced by the GCPVSs is estimated with the calculation procedure of the Table V. The radiation information is obtained from the HelioClim-1 database available at SODA-ESRA [SE08]. From this database, the geographical area to be analyzed is comprised between $-10°$ to $10°$ of longitude, and $30°$ to $45°$ of latitude.

III. RESULTS

Combining these data sources, the tables VI and VII is composed. All the energetic quantities are values of primary energy normalized to the nominal power of the PV generator. The EPBT is used as the metric for comparisons.

Boxplot figures[4] are included in order to show the behaviour of the EPBT in

[4] In descriptive statistics, the five-number summary of a data set consists of: the minimum (smallest observation); the lower or first quartile (which cuts off the lowest 25% of the data); the median (middle value); the upper quartile or third quartile (which cuts off the highest 25% of the data); the maximum (largest observation). A boxplot is a convenient way of graphically depicting groups of numerical data through their five-number summaries. Boxplots can be useful to display differences between populations without making any assumptions of the underlying statistical distribution. The spacings between the different parts of the box help indicate the degree of dispersion (spread) and skewness in the data, and identify outliers.

the whole range of latitude and radiation (figures 2 to 5). Lastly, the comparative of EPBTs between tracker technologies versus the global horizontal radiation is shown in a scatterplot (figures 6).

IV. DISCUSSION

According to the table VI, approximately three quarters of the energy required during manufacturing and installation phases are devoted to the photovoltaic generator. In second place we find the energy required for the support structure and foundations. Due to the wind requirements in double-axis column trackers (height, large surface exposed to wind forces, only one support point, etc.) this contribution is considerably higher than the energy required by fixed systems. However, the energy requirements for structure and foundations of horizontal axis trackers are very similar to the fixed systems amounts: the structure is supported by an axis parallel to the ground, with several support points, and located at low height and then less exposed to wind forces, reducing requirements of concrete and steel. The importance of the rest of items is secondary. It is worth to stress that, although it is necessary to dedicate higher amounts of wire in double axis tracker systems —due to the higher requirement of terrain in order to avoid mutual shadows– the global influence is insignificant.

As recognized by other authors, a PV system is able to produce back the energy required for its existence several times during its life cycle. The figures 2 to 4 show a set of values of EPBT in a range of 2 to 5 years for the conditions of the defined geographical area, depending on the tracking method and the latitude[5]. Therefore, a GCPVS is able to give back the energy required for its existence between 6 to 15 times during its life cycle, supposing a useful life of 30 years. These numbers agree with the conclusions of several papers of the reviewed bibliography.

[5] To provide a context it is worth mentioning the EPBTs results of [MK02]: 4 years for a gas turbine, 6 years for an amorphous silicon PV system, 11 years for the coal technology and 16 years for wind systems. The higher value for the PV system in this document is mainly due to the lower efficiency of the amorphous silicon.

The figures 5 and 6 show that, in the range of latitude and global irradiation of the defined geographical area, and from the EPBT point of view, both tracking methods are preferable to fixed systems. Only for high latitudes the fixed systems are near the tracking technologies in EPBT terms. Therefore, the lower productivity of a fixed system is not compensated by the lower requirement of energy during its life cycle. Using again the table VI, the great importance of the PV generator makes advisable to dedicate more energy to some components of the system in order to increase the productivity of the system and to obtain a higher performance of the component with the highest energy requirement. Both double axis and horizontal axis tracker follow this way, requiring more energy in metallic structure, foundations and wiring, but this higher contribution is widely compensated by the better productivity of the system.

The comparison between tracking methods shall be analyzed carefully. Double axis tracker are preferable with high latitudes (figure 5) and low irradiation (figure 6). Differences between double axis and horizontal axis systems EPBTs values span between 9 and 15%. The source information for these figures (effective irradiation, produced energy and required energy) is subjected to an uncertainty which can be even higher than these differences. Thence, when choosing between these two tracking methods from the EPBT point of view, these comparative figures should be used only as a first step. It is advisable to carry out a more detailed analysis for the location in study and to include some other criteria for the final decision (higher income due to better productivity of double axis systems, better occupation of the terrain of horizontal axis systems, etc.).

V. CONCLUSION

A review of existing studies about LCA of PV systems has been carried out. The data from this review have been completed with our own figures in order to calculate the EPBT of double and horizontal axis tracking and fixed systems. The results of this metric span from 2 to 5 years for the latitude and global irradiation ranges of the geographical area comprised between -10° to 10° of longitude, and 30° to 45° of latitude. With the caution due to the uncertainty of the sources of information, these results mean that a GCPVS is able to produce back the energy required for its existence from 6 to 15 times during its life cycle.

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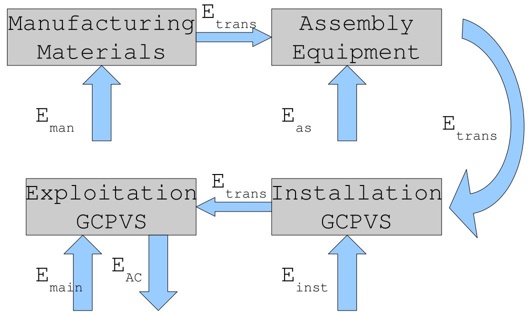

Figure 1: Flow of energy along the manufacturing, installation and exploitation of a GCPVS. The dismantlement and recycling phase has not been included in this cycle. E_{man} stands for the energy required for the manufacturing of the materials, E_{as} for the energy required for the assembly of the main components, E_{inst} for the energy used during the installation and start-up phases, E_{main} for the energy used for the maintenance of the system, E_{trans} is the energy consumption when transporting materials and components between the different phases of the project, and finally E_{ac} is the energy produced by the GCPVS during its life cycle.

Table I: List of Projects which have been analysed. These projects have been designed and installed by Isofoton in Spain concerning double axis tracking, horizontal North-South tracking and fixed systems.

#	Latitude	PV generator	Inverters	Support structure	Wiring
1	36,8	832 kWp	7·100 kW	Fixed	0,4 m^3 Cu
2	37,5	1 152 kWp	10·100 kW	Fixed	0,35 m^3 Cu
3	37,4	6 020 kWp	225·25 kW	225 Double-axis trackers	0,17 m^3 Cu 11,52 m^3Al
4	37,5	2 064 kWp	18·100 kW+1·80 kW	75 Double-axis trackers	0,04 m^3 Cu 4,55 m^3Al
5	36,2	14 069 kWp	123·100 kW	246 Horizontal N-S trackers	8,1 m^3 Cu

Table II: Technical characteristics of an average module manufactured by Isofoton. All the amounts are referred to a nominal PV power of 1 kWp.

Parameter	Amount	
Efficiency	12,4	%
Weight	110	kg
Frame weight	23	kg
Proportion of recycled aluminum	60	%
Glass	69,1	kg
EVA	7,9	kg
Tedlar	1,9	kg
Cell	7,36	m^2
Required Energy	39 840	MJ

Table III: Technical characteristics of the inverters included in the set of projects. These three inverters include a low voltage transformer. The estimated embodied energy includes the replacement of 10% of the equipment once every 10 years. The average inverter includes the embodied energy in the building for the 80 kW and 100 kW inverters.

Equipment	Weight (kg)	Embodied Energy	
Ingeteam 25	320	22 630,95	MJ/inverter
Ingeteam 80	1 180	83 451,65	MJ/inverter
Ingeteam 100	1 250	88 402,17	MJ/inverter
Average Inverter	-	1 124,33	MJ/kW

Table IV: Technical characteristics of the Fixed and Tracking structures included in the set of projects.

	Isotrack25	Ades6f22m	Horizontal N-S	Fixed
PV power	27,32	27,32	59,62	1
Structure weight (kg)	7 150	7 500	10 464	128,13
Tracking mechanisms weight (kg)	210	180	100	0
Concrete foundation volume (m^3)	38,85	18,00	32,51	1
Steel foundation volume (m^3)	0,49	0,19	0,34	0
Yearly energy consumption (kWh/kWp)	13	7	4	0

Table V: Calculation procedure for the estimation of energy produced by a PV system from 12 monthly means of daily global horizontal irradiation data

Step	Method
Decomposition of 12 monthly means of global horizontal daily irradiation	Correlation between diffuse fraction of horizontal radiation and clearness index proposed by Page [Pag61]
Estimation of instantaneous irradiance	Ratio of global irradiance to global daily irradiation proposed by Collares-Pereira and Rabl [CPR79]
Estimation of irradiance on inclined surface	Method of Hay and Davies [HM85]
Albedo irradiance	Isotropic diffuse irradiance with reflection factor equal to 0,2
Effects of dirt and angle of incidence	Equations proposed by Martin and Ruiz [MR01]. A low constant dirtiness degree has been supposed.
Ambient Temperature	The ambient temperature has been modeled with the constant $T_a = 25°C$.
Parameters of the PV generator	$dV_{oc}/dT_c = 0,475\frac{\%}{C}$ $TONC = 47°C$
Efficiency of the Inverter	The characteristic coefficients of the inverters [JSS92] are: $k_0^o = 0.01$, $k_1^o = 0.025$, $k_2^o = 0.05$.
Wiring and electrical protections	Losses in wiring and electrical protections have been modeled with constant coefficients according to local regulations.

Table VI: Energy required by the main components of different GCPVS. All the amounts are referred to a nominal PV power of 1 kWp.

	Double Axis		Horizontal N-S Axis		Fixed	
Component	(MJ_p/kWp)	(%)	(MJ_p/kWp)	(%)	(MJ_p/kWp)	(%)
Module	41 819	69,54%	41 819	78,67%	41 819	81,99%
Support Structure	9 329	15,51%	6 108	11,49%	4 459	8,74%
Tracking mechanisms	248	0,41%	58	0,11%	0	0,00%
Foundation (steel)	3 371	5,61%	1 536	2,89%	0	0,00%
Foundation (concrete)	2 445	4,07%	1 281	2,41%	2 352	4,61%
Transport	1 339	2,23%	900	1,69%	1 037	2,03%
Inverter	1,091	1,81%	1 091	2,05%	1 091	2,14%
Wiring	497	0,83%	364	0,68%	248	0,49%
Total	60 140	100%	53 157	100%	51 005	100%

Table VII: Statistical summary of EPBT values of tracking and fixed systems calculated over the geographical area comprised between $-10°$ to $10°$ of longitude, and $30°$ to $45°$ of latitude.

EPBT	Min	1st. Quartile	Median	Mean	3rd Quartile	Max
Double-Axis	2,1	2,4	2,6	2,7	2,82	4,34
Horizontal-NS	2,3	2,65	2,88	3	3,17	4,9
Fixed systems	2,68	3	3,22	3,3	3,45	4,8

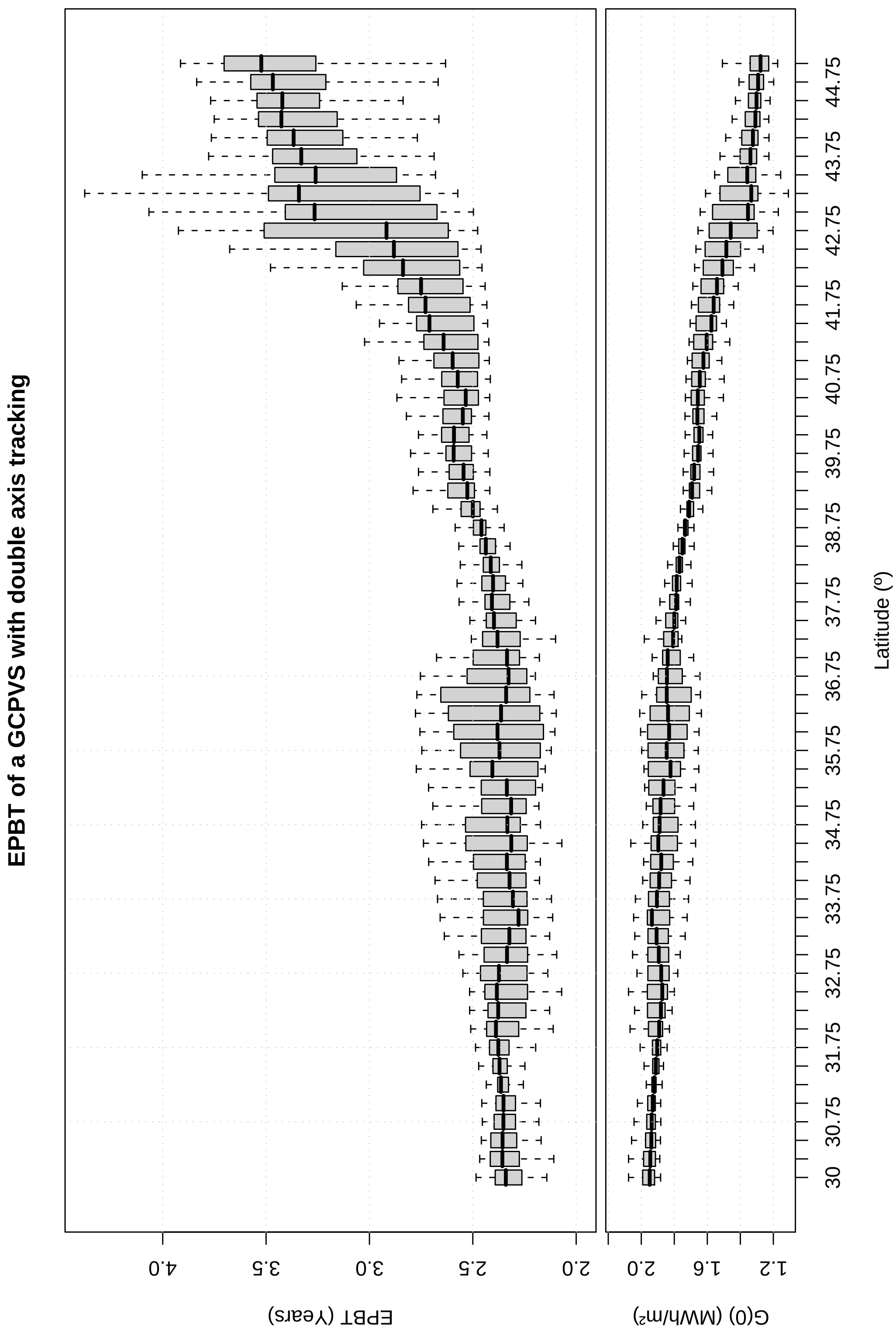

Figure 2: EPBT of a GCPVS with double axis tracking calculated over the geographical area comprised between -10° to 10° of longitude, and 30° to 45° of latitude. The bottom frame of this figure shows the yearly values of horizontal global irradiation as a reference.

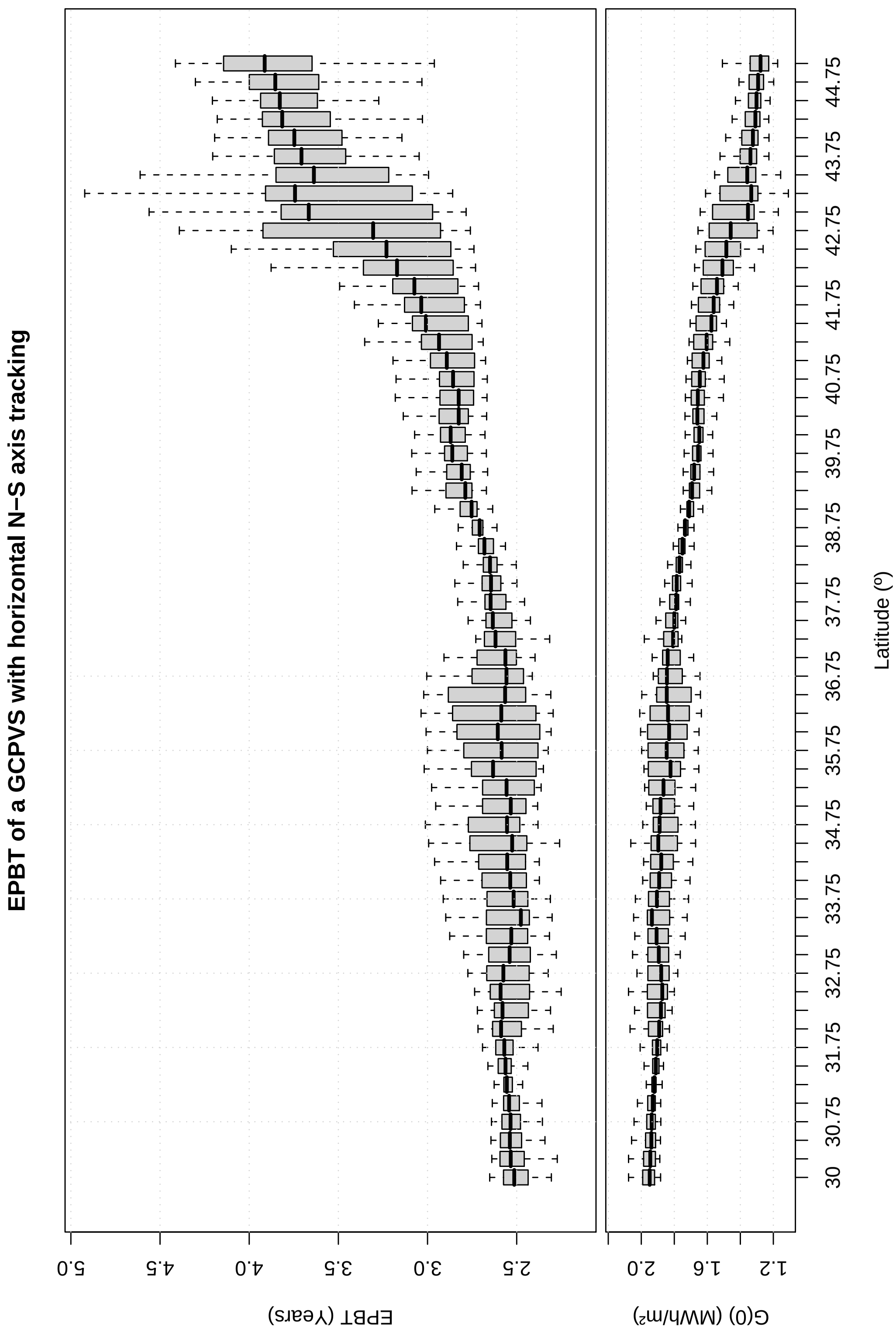

Figure 3: EPBT of a GCPVS with horizontal N-S axis tracking calculated over the geographical area comprised between $-10°$ to $10°$ of longitude, and $30°$ to $45°$ of latitude. The bottom frame of this figure shows the yearly values of horizontal global irradiation as a reference.

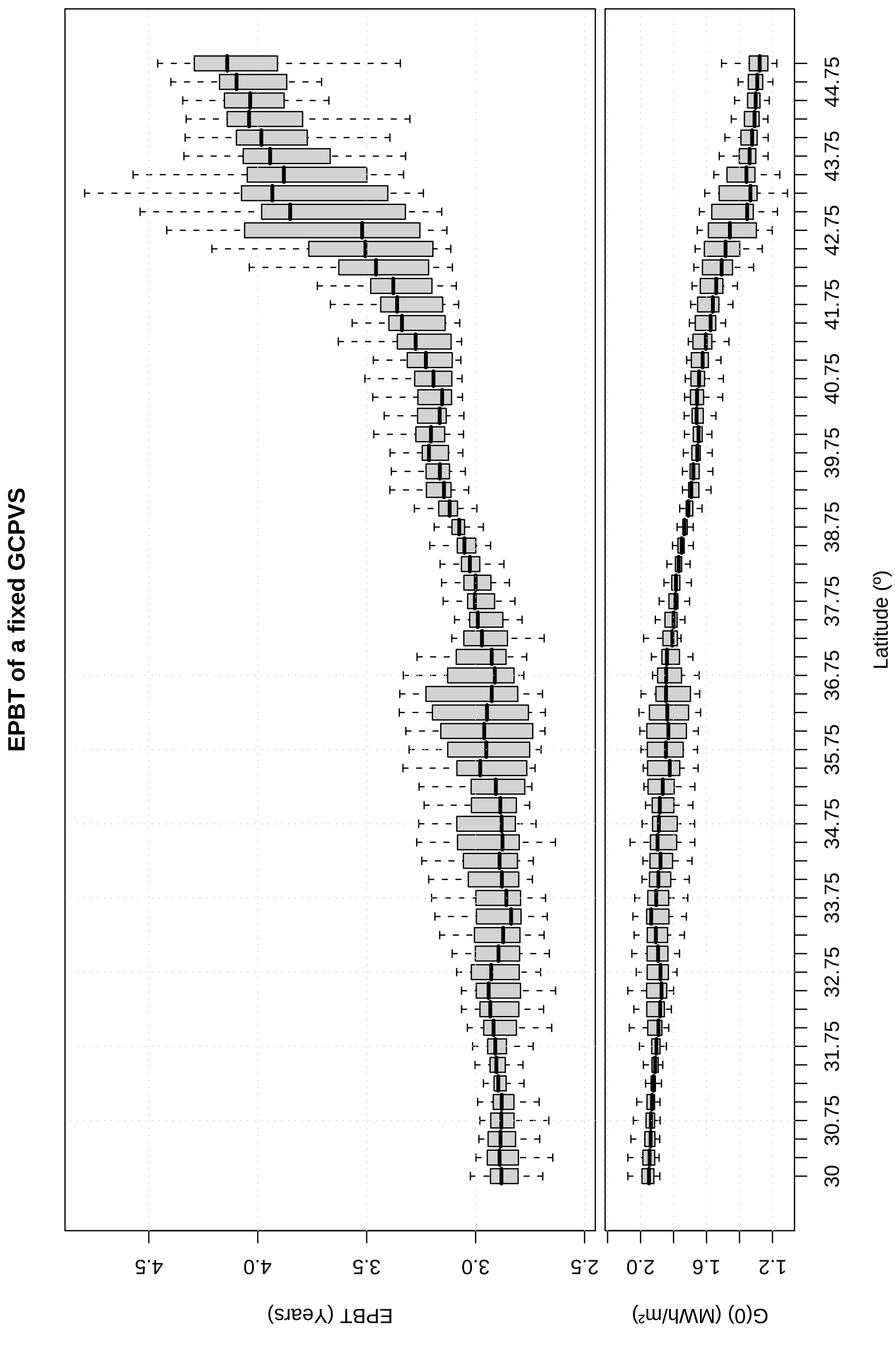

Figure 4: EPBT of a fixed GCPVS calculated over the geographical area comprised between -10° to 10° of longitude, and 30° to 45° of latitude. The bottom frame of this figure shows the yearly values of horizontal global irradiation as a reference.

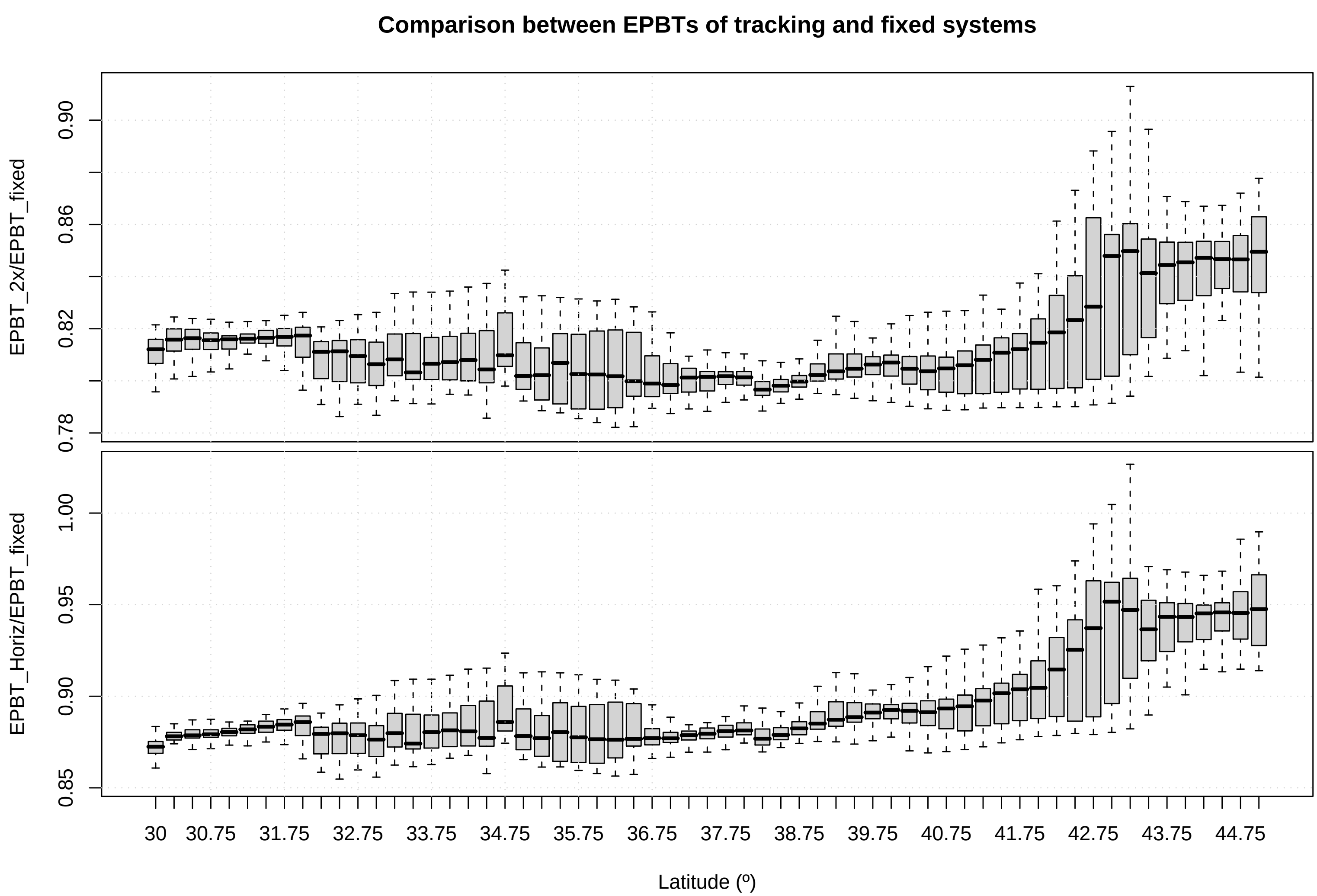

Figure 5: Comparison between EPBTs of double-axis tracking and fixed systems (top frame) and horizontal N-S tracking systems and fixed systems (bottom frame) calculated over the geographical area comprised between -10° to 10° of longitude, and 30° to 45° of latitude.

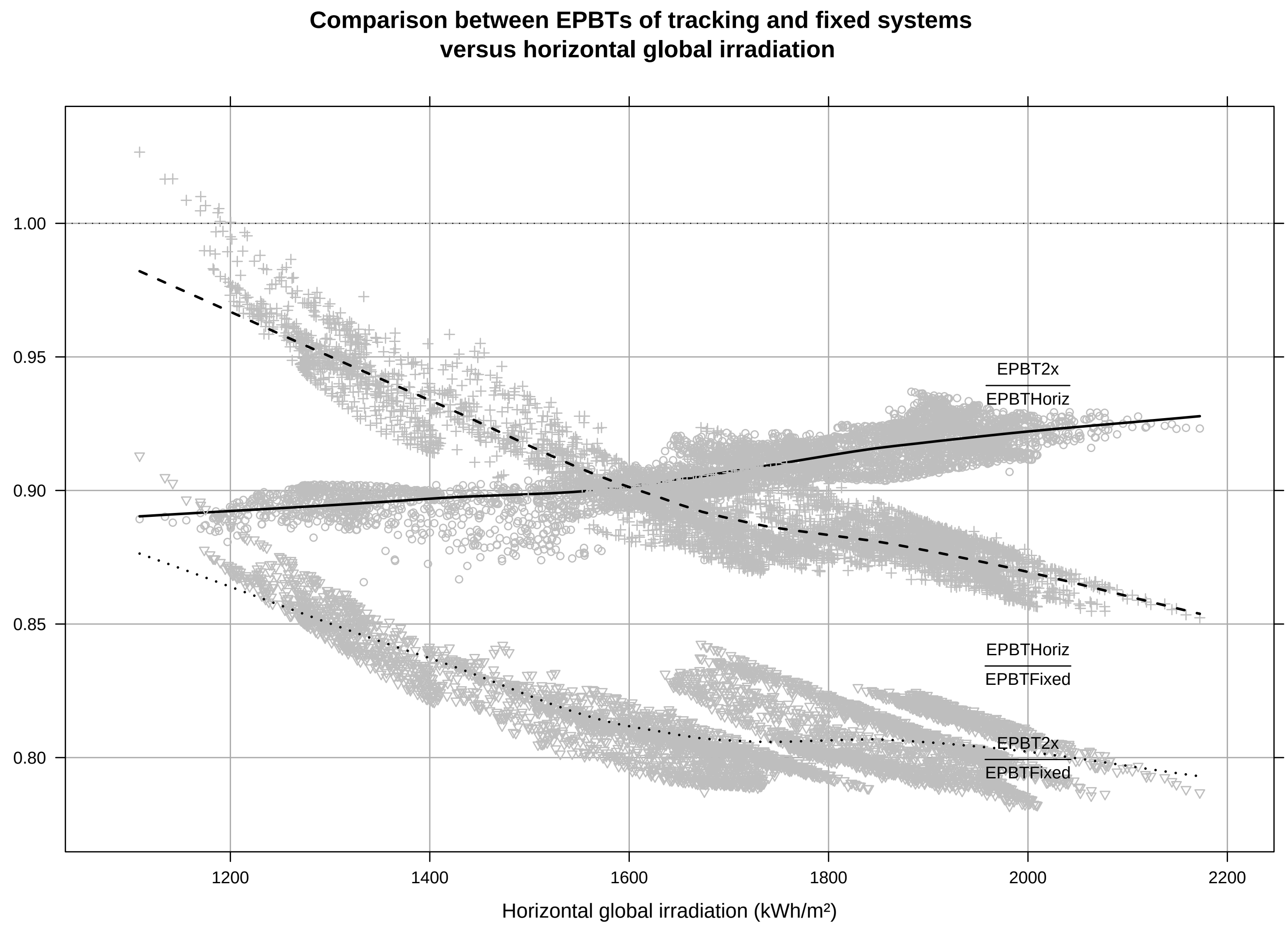

Figure 6: Comparison between EPBTs of double-axis tracking (EPBT2x), horizontal N-S tracking (EPBTHoriz) and fixed systems (EPBTFixed) vs. yearly horizontal global irradiation calculated over the geographical area comprised between -10° to 10° of longitude, and 30° to 45° of latitude.