# SOLAR ENERGY BREEDERS

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ABSTRACT: Photovoltaic (PV) will be one of the most important energy sources in the future. Deciding which fraction of energy supply PV can occupy in the future, not only the calculation of the energy amount PV systems can produce is needed but also the energy demand of PV systems to build them is required. This paper includes an energy scenario from 1970 to 2050 which is generated by using energy learning curves of PV systems and the solar breeder concept. The calculation shows how much net energy PV systems delivered in the past and can deliver in the future. In the next step also wind power and hydro power are considered within the solar breeder concept and furthermore after 2010 the additional energy demand for storage is considered being necessary when PV and wind power plants will become an important part in energy supply.
Keywords: Energy Performance, Photovoltaic, PV Market, Storage, Solar Breeder, Modelling, Energy Supply 2050

## 1 INTRODUCTION

Photovoltaic is one of the fastest growing renewable energy sources. The reasons are on the one hand the cost reductions of PV systems and on the other hand the increasing need for sustainable power supply. That is the reason why PV power systems will become an important part of energy supply in the future. But to which extend and dynamic can PV systems contribute to the global energy transformation? Including the cumulated energy demand (CED) of new PV systems "breeded" by already existing ones. This problem can be solved by the solar energy breeder concept, first published by Slesser and Hounman in 1976 [1]. But until now it has not yet been considered in any scenarios for the energy supply in the future. A solar breeder is a device which generates enough energy to produce more energy than needed for the own production, hence new net capacity of energy generation. Therefore no other energy sources are needed. Solar breeders grow energetically in their capacity by themselves.

The purpose of the presented work is to calculate a scenario for energy supply till 2050 and to analyse energy supply in the past since 1970 by using the energy breeder concept not only for PV but also for the other two major renewable energy technologies: wind power and hydro power. In addition, also the energy demand for storage of PV and wind generated electricity is considered.

## 2 DEFINITION SOLAR BREEDER

In 1976 Malcom Slesser and Ian Hounman introduced the solar breeder concept [1]. According to them an "energy breeder" is "a device which 'breeds' capacity to generate useful energy without consuming energy stocks" [1]. Therefore a "solar breeder" is then a device which generates energy by using solar energy like PV, wind power or hydro power. In conclusion a device is only an energy breeder if it produces more energy during its lifetime than needed to maintain and rebuild it. This includes all needed indirect and direct energy "from cradle to grave" for this device. A part of the surplus of energy can be used to build more devices. This is the "reinvestment energy" which is needed for the growth of the capacity. The rest of the generated energy is called "net energy" and is the real energy which can be used to fulfil the energy demand needed (figure 1). An annual calculation of this energy consideration can be done by equation 1. A more detailed introduction of the mathematics for the solar breeder concept can be found in [2].

$$C(t+1)=C(t)+r(t)\cdot\frac{\Delta t}{EPBT(t)}\cdot C(t)-r(t-L)\cdot\frac{\Delta t}{EPBT(t-L)}\cdot C(t-L)$$

**Equation 1:** Discrete model describing the growth of solar energy breeders. Abbreviations stand for: PV capacity, *C*, reinvestment rate, *r*, time interval in years, *t*, Energy Pay Back Time in years, *EPBT*, and lifetime of power plant systems in years, *L*. [2]

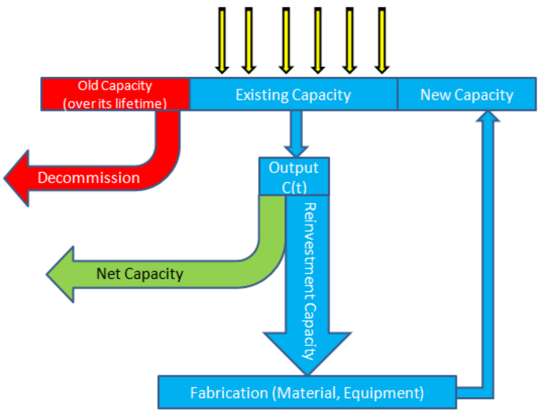


**Figure 1:** Solar Breeder Concept

## 3 SOLAR BREEDER CONCEPT FOR PV

### 3.1 Construction of PV Modelling

In this work, the solar breeder concept is calculated for every year from 1970 to 2050 by equation 1. The amount of energy generated by the PV systems is calculated and annually reinvested to produce new capacity in the following year. At the end of each year power plants which had reached the end of their lifetime are decommissioned in the model. For a more detailed analysis the following six major regions are considered: the Americas, Europe, Africa, China, India and Rest of Asia. First the model is calculated for each of these regions individually and then the single results are integrated on a global scale.

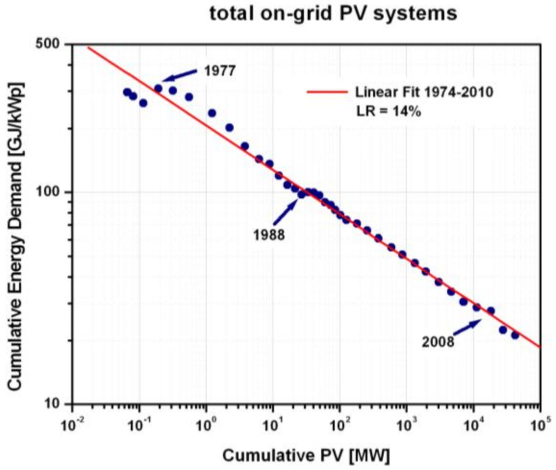


**Figure 2:** Energy learning curve of PV systems from 1974 to 2010 [3]. Energy demand is calculated by energy learning curves of PV modules for different PV technologies and BOS components weighted relative to their share in PV module and system market. PV modules show a decreasing energy demand over the last decades. From 1974 to 2010 the energy learning rate has been 14%.

An important part for the discrete model by equation 1 is the Energy Pay Back Time (EPBT). For a more detailed analysis an annual time-resolved function for the EPBT is necessary. This can be done by the general energy learning curve of PV Systems (figure 2) [3]. This learning rate includes for every year the average energy demand of a PV system. Thereby it considers the share of different PV cell and system technologies in each year which leads to an annual average energy demand of PV systems. The construction and theory of this learning rate is discussed elsewhere [3].

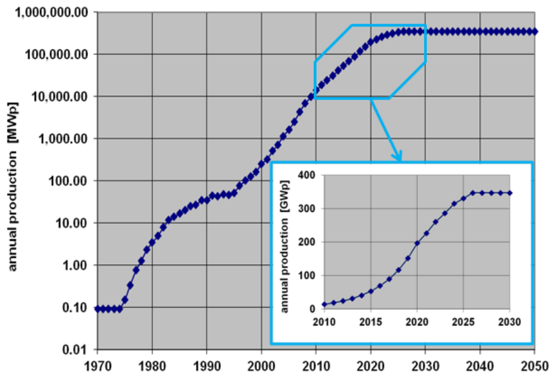


**Figure 3:** Annual PV production from 1970 to 2050. Data for the years 1970 to 2010 are taken from [4].

For the years 1970 to 2010 the annual PV growth is used [4]. After 2010 annual PV capacity growth is assumed to be 30% p.a. till 2020. After 2020 it is reduced to 15% (2021-2022), 10% (2023-2024) and 5% (2025-2026). From 2027 to 2050 annual PV capacity production is assumed to be constant at 347 GW p.a. (figure 3). Lifetime was assumed to improve from 20 to 50 years from 1970 to 2050 and average performance ratio from 62% to 84%. For irradiation on fixed optimally tilted module surface population weighted irradiation is chosen [5]. Energy demand scenario for the decades to come is developed according to the "advanced scenario" by Greenpeace and EREC [6].

3.2 Results

From 1970 to 1991 global PV power system installations consumed more energy for their production than what they have generated. The first time PV power systems generated net energy was in 1992.

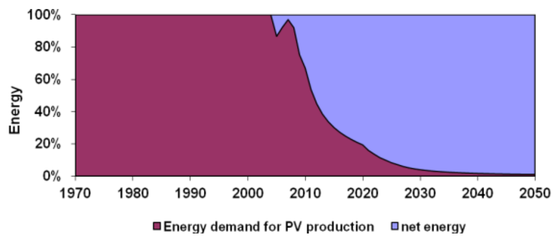


**Figure 4:** Ratio of required energy for new PV production to net energy from total generated energy of PV systems. Though already 1992 net energy existed, the net energy from 1992 to 2004 has been needed to compensate the additional energy demand for PV production from 1970 to 1991. In this time period more energy were needed than generated. The first time in 2005 real net energy was generated.

Summing up all energy demand and generation since 1970, PV power systems were energetically amortised in 2005 (figure 4). Since 2005 PV systems have always generated net energy for society in parallel to producing new PV capacity. Therefore PV is a solar energy breeder.

Figure 4 also shows that in future the ratio between energy demand for PV production and net energy for society demand will dramatically change. The reason for this is that on one hand the performance of PV systems will increase and on the other hand the energy demand for PV systems will decrease. This process was noticed since 1970. Although the absolute values will not change as fast as it was in the past, every improvement will have a high influence on the ratio between energy demand and net energy. The reason is that since 2005 all surplus energy demand of the past has been paid back by the PV itself. Since 2005 the technology state of the art has been sufficient, so that PV can 'breeds' itself and still delivers net energy for society.

Figure 5 shows the absolute value of net energy which is available to be delivered by PV. This result is the summary of the six major regions. Firstly net energy has been considered in the single regions. Thereby the calculated capacity is divided according to its ratio to the energy demand in the respective regions according to [6]. Figure 5 shows that PV can deliver around 30% of the worldwide energy demand till 2050, only by considering the total net energy production.

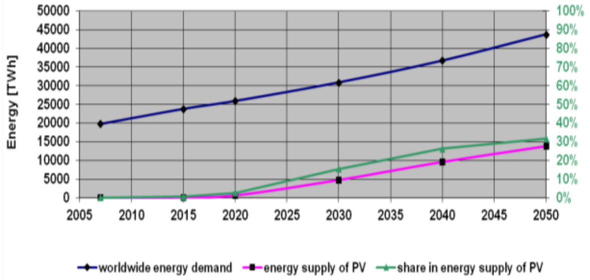


**Figure 5:** Development of net energy of PV in proportion to global energy demand for the years 2007 to 2050, calculated by the solar energy breeder concept. For the development of energy demand the "advanced scenario" of Greenpeace and EREC is taken (blue line) [6]. The pink line shows the absolute energy generated by PV. The green line shows the development of relative share in total needed energy supply. After 2027 the annual production of PV power systems is set constant.

## 4 EXPANSION OF SOLAR BREEDER CONCEPT

For judging the real potential of PV an expansion of the solar breeder concept is necessary. Thus also hydro and wind power are analysed by the solar breeder concept to get a more comprehensive energy scenario. In contrast to PV, no energy learning curve exists for them. Therefore other methods for the EPBT have been chosen.

### 4.1 Construction of Wind Power Modelling

Beside PV also wind power is a renewable energy source with a high growth rate. A huge advantage of wind power in connection with PV is that both energy sources do not have high overlap during their energy production [7]. Both fluctuating energy sources complement one another very well. In most regions of the world the critical overlap of their full load hours (FLh) is only between 1% - 3% [7].

Due to the missing energy learning curve an exponential fit for a normalised EPBT is defined. For a FLh of 2000 h/y the normalized EPBT accounts between 15 and 0.25 years for the time period of 1970 to 2050. EPBT could be calculated for every year and every region by using adequate FLh. Thereby the range of the FLh has reached from 1917 h/y for India in 1970 up to 3234 h/y for the Americas in 2050. Values are generated by considering different investigations about FLh for wind power [8, 9, 10, 11].

Annual wind power capacity production is assumed to grow by 25% p.a. for the years 2014 to 2020. It is reduced to 10% (2021-2022), 5% (2023-2024) and 3% (2025-2026). After 2027 the annual installed capacity is set to be constant at 337 GW p.a.. The lifetime is chosen to be 15 y in 1970. Then a linear growth up to 20 y in 2000 is assumed. From 2010 to 2030 it increases from 20 y to 25 y and finally a lifetime of 30 y in 2050 is taken into account. All assumptions are justified by different investigations about wind power plants [9, 10, 11].

### 4.2 Results for Wind Power

The calculation of wind power within the solar breeder concept shows that also wind power is a solar breeder. In contrast to PV, wind power is energetically amortized in the year 1994. From 1970 to 1983 wind power consumed more energy than it delivered. This energy was paid back between 1984 and 1994 due to the surplus of energy within this period of time. However, in the Americas wind power has the highest potential. Here wind power delivered in 2007 a net energy of 26.7 $TWh_{el}$, which was equal to 0.4% of the total energy demand in this year. Till 2050 wind power in the Americas can deliver around 60% or 6,530 $TWh_{el}$. Worldwide wind power is able to deliver around 47% of energy demand in 2050 (figure 6).

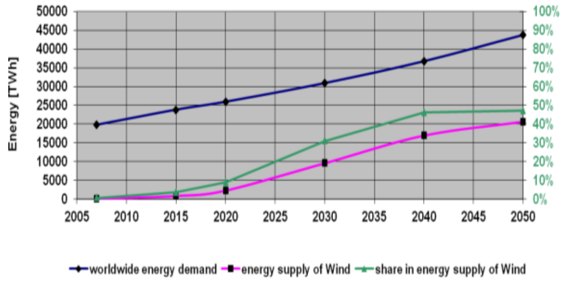


**Figure 6:** Development of net energy of wind power in proportion to global energy demand for the years 2007 to 2050, calculated by the solar energy breeder concept. For the development of energy demand the "advanced scenario" of Greenpeace and EREC is taken (blue line) [6]. The pink line shows the absolute energy generated by wind power. The green line shows the development of relative share in total needed energy supply. After 2027 the annual production of wind power systems is set constant.

When PV and wind power are considered together, all power plants have been energetically amortized in 1995 and thus they will be able to deliver up to 34,490 $TWh_{el}$ or 78.9% of the worldwide energy demand in 2050.

### 4.3 Construction of Hydro Power modelling

The advantage of hydro power is that it is not a fluctuating energy source. Hence, for a substantiated energy scenario, a non fluctuating energy source is necessary. Additionally hydro power is a established energy source.

For the years 1970 to 2008 capacity of hydro power is taken from [12]. Thereby, the constructed hydro power plants before 1970 were cumulated and added to the energy balance in 1970. Growth rate for the future was assumed to be very slow. After 2008 the growth rate of the annual cumulated capacity was assumed to decrease from 3% in 2009 and 2010 to 2% for the years 2011 to 2030 and finally to 1% for the years 2031 to 2050. Thereby, the ratio of the capacity for the single regions was assumed to be constant except for the Americas and Europe. There the capacity was assumed to decrease in ratio to the other regions. In conclusion, the capacity of worldwide hydro capacity was 241 GW in 1970 and is assumed to be 1,463 GW in 2050 and new hydro power capacity is assumed to be around 15 GW p.a. after 2010.

In addition a constant EPBT of 1 year and a constant average lifetime of 80 y are assumed. However, the lifetime has no significant influence in this case. The reason is that the considered time period is only 80 years, which is not a long period for hydro power stations.

FLh is calculated by [13] and is also assumed to be constant. Their values are between 3,298 h/y for India and 4,716 h/y for China.

### 4.4 Results for Hydro Power

Also hydro power is a solar energy breeder. However, this energy source is energetically amortized since 1970 and therefore it has produced net energy since then. It can deliver a constant net energy of around 14%-16% of worldwide energy demand in future (figure 7). Thus hydro power has a high potential to save a constant energy demand.

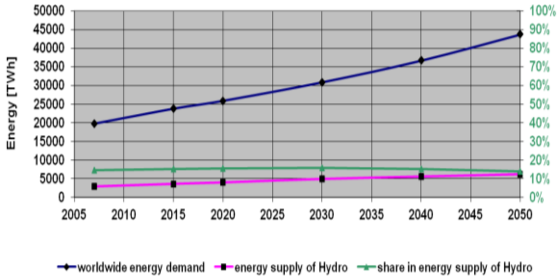


**Figure 7:** Development of net energy of hydro power in proportion to global energy demand for the years 2007 to 2050, calculated by the solar energy breeder concept. For the development of energy demand the “advanced scenario” of Greenpeace and EREC is taken (blue line) [6]. The pink line shows the absolute energy generated by hydro power. The green line shows the development of relative share in total needed energy supply.

When the net energy of the three reviewed renewable energy sources are summed up, this system has been energetically amortized since 1970. This means that the net energy of hydro power and later also of wind power were sufficient to be invested in new PV systems during the period of 1970 till 1991. Therefore, at the beginning additional energy for PV was produced by renewable energy sources. They produced enough energy to make production of PV possible. Hence, PV has never been dependent on fossil fuel.

Comparing the ratio of net energy of the three energy sources shows that (till today) PV and wind power have not had noticeable participation to the net energy consumed by society. This will change in the future (figure 8). Since 2000 the ratio of PV and wind power for net energy share has increased continuously relative to hydro power. In the future PV and wind power will be able to produce much more net energy than hydro power.

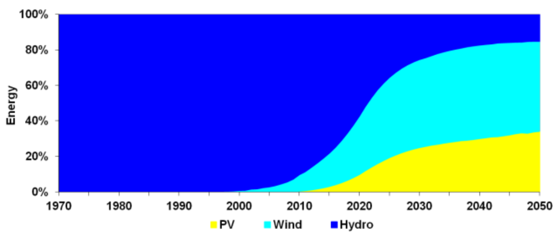


**Figure 8:** Relative share of produced net energy by PV (yellow), wind power (turquoise) and hydro power (blue) from 1970 to 2050. Net energy is calculated by solar energy breeder concept.

## 5 CONSIDERATION OF STORAGE

The results of the energy breeder concept show that PV and wind power might have a major fraction in energy supply in the future. Since these energy sources fluctuate, storage systems are necessary. Therefore, from the previously calculated net energy, energy for storage systems has to be deducted from it. Only the remaining energy is the real net energy for society

### 5.1 Construction of Storage Modelling

According to Denholm and Kulcinski [14], it is possible to deliver 20% of the energy demand of a region without storage system, when using fluctuating energy sources. Therefore energy for storage system is considered, when PV and wind power deliver more than 20% of the energy demand for the selected six regions.

Already existing storage systems are the pumped hydro storage power stations (PHS). The operating PHS capacity which was built till 2008 is calculated by Platts [12] and is also listed by the regions. The available worldwide PHS capacities are 110.58 GW, which are equal to approximately 425 TWh storage.

Every additional storage capacity has to be built. Therefore an average lifetime and energy demand for storage capacity is determined. The average includes PHS and electrochemical storage, which are weighted in ratio 1:4. The reason is that in future local small to medium storages will be needed for PV and wind power. Analyzing different storage systems [14, 15] leads to an average lifetime of 28 years and an energy demand of 163 $GWh_{el}$ for every $GWh_{el}$ storage.

Furthermore a storage factor was considered. The amount of energy that has to be stored in one year does not have to be stored all at the same time. The storage capacity can be smaller than the stored energy amount of a year. According to Hofmann et al. [16], the maximum of storage capacity is around 0.5% to 8% of the stored energy. Relating to the different assumption comparing to [16] and the different reviewed regions, storage factor was assumed to be 5%.

It should be mentioned that the assumption of storage capacity was only a first try to consider storage in the solar breeder concept. For a more detailed analysis, more information about energy demand for storage and the storage factor is necessary. However, nowadays publications do not offer them. Furthermore, a detailed calculation on an hourly basis for the resources and the load would be needed.

### 5.2 Results for Storage

Considering the demand of storage, it was calculated that till 2026 the already available storage capacity of PHS is sufficient but for 2027 additional storage capacity is necessary.

In average, it is assumed that one year is required to build new storage systems. This means that for the additional storage capacity in 2027 the energy demand for this additional storage has to be subtracted from the net energy. In conclusion, 2% of the net energy in 2026 is needed for additional storage for 2027. However, the demand of storage will increase. It was calculated that

23% to 35% of the net energy will be needed for new storage capacity between 2027 and 2037. However, 5% to 30% will be needed for storage between 2038 and 2050. In conclusion, more than 70% of original net energy will be used for society demand except for some years. The analysis shows that a time observation for storage has only a small influence on energy supply.

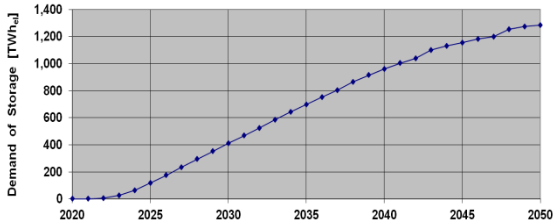


**Figure 9:** Average demand of storage capacity per year. It is assumed that 20% of energy demand in every region can be covered by fluctuating energy sources without storage considering that PV and wind power do not show a significant critical overlap [7]. Additionally it is considered that the storage capacities can be used more than once per year. That leads to a storage dimensioning of 5% storage capacity in relation to total annual energy demand. The lifetime of storage facilities is assumed to be in average 28 years considering both mechanical and electrochemical storages.

## 6 Final Energy Scenario 2050

Considering PV, wind power and hydro power within the solar breeder concept and the additional energy demand for storage leads to a well-founded energy scenario. This scenario includes only the real net energy for society.

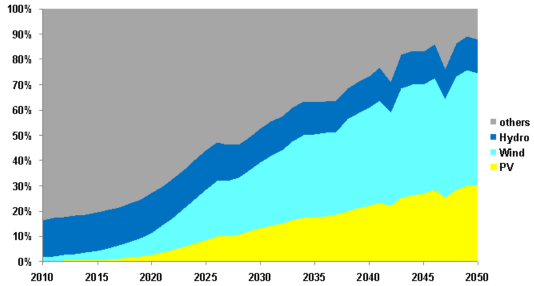


**Figure 10:** Ratio of PV, wind power and hydro power to annual energy supply, considering that the additional energy demand of storage capacities is totally satisfied by generated energy of PV, wind and hydro power plants. Fluctuations are induced by a different demand of storage in the different regions.

Results for each region indicate that Europe, China and the Americas can theoretically satisfy their total energy demand from PV, wind and hydro power. In the other regions three factors limit this kind of energy supply. Firstly, Africa and India have no sufficient FLh for wind power. Secondly, India and Rest of Asia have no sufficient FLh for hydro power and third Rest of Asia has not so efficient irradiation. Therefore the renewable energy sources are theoretically able to deliver 54% (India), 63% (Africa) and 70% (Rest of Asia) of the energy demand in 2050. However, the regions with the highest energy demand can totally be supplied energetically by the three renewable sources. This shows the high potential for PV, wind and hydro power in these regions and also the high potential of the renewable energy sources.

In conclusion, the analysis shows that worldwide up to 88% of energy demand can be delivered by PV, wind and hydro power till 2050 (figure 10) or 38,330 $TWh_{el}$/y. Therefore, the share in energy of conventional power plants into the energy supply, which was worldwide over 80% in 2010, can be reduced to around 12% in 2050. This will happen when the annual PV and wind capacity installation be constant after 2027 (a very moderate assumption). Therefore, the gained results can be considered as the minimum potential of the PV, wind and hydro power since the results include the following factors:

- Annual PV and wind power capacity will not increase anymore after 2027.
- New PV, wind and hydro power plants are completely energetically produced by the power plants which exist in the respective year. However, no energy source uses energy from another source to produce new power plants.
- The additional energy demand for storage is completely delivered by PV, wind and hydro power plants.
- PV, wind and hydro power plants which reach the end of their lifetime are deleted at the end of the respective year and do not produce any energy after this year anymore.

## 7 CONCLUSION

PV is a solar energy breeder which has always generated real net energy since 2005. Reducing energy demand of PV systems leads to an increasing amount of net energy. In addition wind power and hydro power can energetically grow by themselves. All three major renewable energy technologies are part of an autonomous system having the capability to cover the global energy demand. In the past only hydro power generated net energy. However, the solar energy breeder concept shows that in future PV and wind power will dominate net energy which is produced by renewable energy technologies. In conclusion, all three renewable energy technologies generate enough energy to reproduce themselves energetically and to produce enough storage capacity. Additionally, at the end there is still enough net energy left to satisfy 88% of world energy's demand. This shows how sustainable PV power systems are and how important they will become for the future.

## 8 ACKNOWLEDGEMENTS

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