PV as a Major Contributor to the 100 Renewably Powered World and Solving the Climate Battle

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Abstract:

This paper aims to demonstrate in a comprehensive yet clearly arranged and short digest how we are able to end an unfair, dangerous, environmentally unfriendly and increasingly expensive energy supply and usage towards a fair, clean and lower cost energy situation for everyone in the future. The important role which Photovoltaics (PV) has to play is emphasized but also the necessary portfolio of other renewables, notably wind, together with the large scale introduction of electricity storage. With today's existing power purchase agreements for PV, wind and also new nuclear power stations it is shown that already with current prices, renewable electricity is 5 to 10 times less expensive compared to new nuclear. Especially the economic argument will quickly drive the development towards a 100% renewably powered world within this century and provide energy at lowest price for everyone, highest security of supply everywhere and helping best to solve the climate battle. This paper is based on a presentation given in Bahrain late 2016 [1].

Today's Energy Situation

In the years around 2010 the world's energy situation is shown in Fig.1 [2]. The primary energy (PE) was around 140 PWh (P = Peta = 10^{15}) and consisted of ~80% fossil and ~5% nuclear exhaustible energy sources. The contribution of renewables – mainly fire wood and hydro – was around 15%. The conversion of primary energy into usable secondary energy (SE, also named Final Energy Consumption) is associated with considerable losses and amounted to ~90 PWh. The highest loss originates from conversion of fossil and nuclear primary energy sources into electricity and is around 2/3 on an average level. The fraction of renewables is increased to ~ 20%. The last column on the right shows the energy content for what we really need: hours of light with a given intensity from a light bulb, transport with a petrol driven car from A to B, comfortable living in well air-conditioned houses, power and process heat for the industry and many more. The machines and devices which convert secondary energy into what we really need have energy losses which decrease the end user energy (EE) to ~40 PWh. There was an old rule of thumb for the relation between these three energy forms: PE : SE : EE = 3 : 2 : 1. This relation has unfavorably changed to 3.5 : 2.3 : 1. It is the goal of this paper to demonstrate that in a renewably powered world this ratio will be ~ 1.5 : 1.5 : 1.

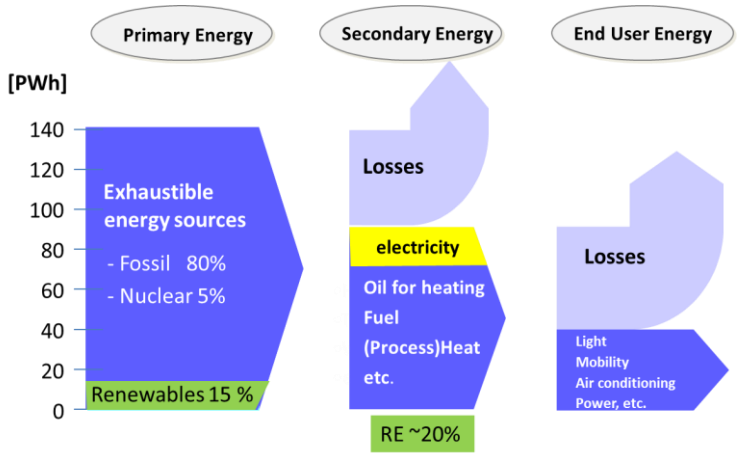

Figure 1: Primary, secondary and end user energy in ~2010

The energy sectors within the SE on a global level are shown in Fig.2 and are 27% for mobility, 28% for low temperature heat, 23% industry (process) heat, 9% industry electricity and 13% rest of electricity. For an easy remembering the fractions can be approximated to ~1/4 mobility, ~1/4 low temperature heat, ~1/4 industry (process) heat and ~1/4 electricity (total).

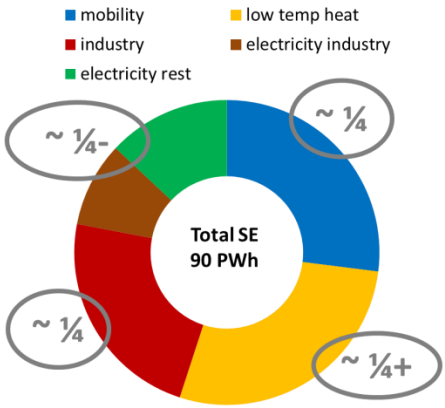

Figure 2: Energy sectors within secondary energy globally (~2010)

Energy Efficiency Measures

Although energy efficiency measures have nothing directly to do with renewable energies they are important as they will be able to increase the fraction of renewables for a given contribution. Two types of efficiency measures are shown in Fig.3: (1) to use machines and devices which convert SE much more efficiently to the needed EE. Examples are LED's instead of light bulbs, electric cars instead of petrol driven ones, phase angle modulated power for the

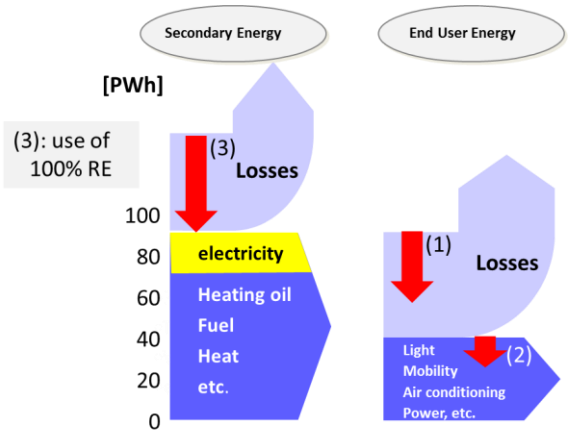

Figure 3: Energy efficiency measures (1 and 2) and removing the losses (3) to obtain secondary energy with renewables

millions of pumps instead of constant power for all flow rates and many more. (2) to provide the specific needs with measures which do not require SE; examples are proper insulation (and ventilation) of houses instead of burning gas for heating or electricity for air-conditioning, thoughtful planning of future urban districts to minimize traffic etc.. The red arrow (3) shows what by convention has been agreed, namely that the SE provided by renewable sources is equal to the PE (the convention for measuring the primary energy content is either the Physical Energy Content Method (PECM) or the Direct Energy Equivalency Method (DEEM); as a physicist I would have equated the PE for electricity from a PV module as the energy content within the solar energy received, i.e. for a 20% efficient solar module, producing 10 kWh electricity, the PE would then be 5 times higher, i.e. 50 kWh – but let us continue with what has been agreed).

There is one important consequence with many of the new and higher efficient devices: in most cases they are more expensive to buy for the same service compared with old and low efficiency products (example LED versus light bulb). Only the total cost over the lifetime of the respective product shows that the service will be cheaper with the new devices by taking into account lower energy consumption and in some cases longer lifetime. So in future it will be no longer as easy as it was in the past by only comparing the investment cost – what is still done in many cases today. Only the total cost over lifetime determines which product delivers a less expensive service. The same argumentation applies also to renewable energies as their specific investment is typically more expensive compared to old fossil and nuclear technologies but they have no fuel and other necessary cost and are therefore less expensive.

It is a straightforward exercise with the examples given and some additional obvious ones to conclude that with today's available machines and devices it would be rather easy to increase the efficiency on average by a factor of 2 – let us call this a "mild" efficiency

increase. It has been shown in recent years by von Weizsäcker et al. [3, 4] that an efficiency increase up to a factor of 5 is feasible – name this “aggressive” increase. In order to be just a bit more ambitious as “mild” and less as “aggressive” we may define a factor of 3 as a “realistic” efficiency increase. This “realistic” efficiency increase includes the change from oil for transportation to electricity and electricity based fuels (hydrogen from hydrolysis and methane by reacting CO_2 with hydrogen, 2 H_2 + CO_2 = CH_4 + O_2). With these assumptions there will be a significant change for the relative share of the energy sectors as shown in Fig.4. In particular the fraction of electricity increases from 22% today towards 54% for a global SE usage with “mild” efficiency measures, although the absolute number increases only by ~20%.

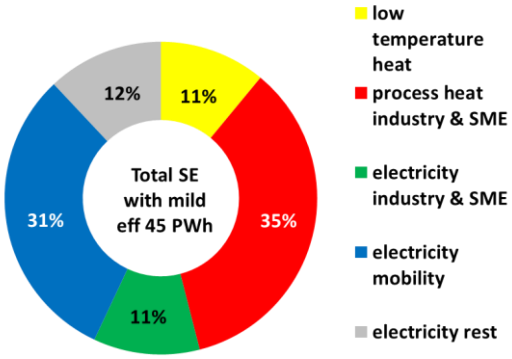

Figure 4: Energy sectors within the global secondary energy using “mild” efficiency measures

Future Energy Needs

The important question arises how many billion people we will have to satisfy with energy. The United Nations [5] have made several scenarios for the future development. The medium one is shown in Fig.5 with an interesting result. While until the 1980s we had a steep increase for the 10 year average of annual population increase, there is since the 1990s a decrease observed. With the assumed a further decrease in the coming decades as shown there is good evidence that the global population towards the end of this century could level off at around 10 billion people.

One important aspect for the future is also to solve the existing inequity for the energy use globally in different regions. If we do not care for a solution we may see emigration of nations at a level which will manifold exceed the immigration to Europe in recent years. A simplified calculation is as follows: When we had ~6 billion people using ~90 PWh SE we had ~1/4 of people using ¾ of SE. From this we can conclude that 1 billion of people enjoying “high-quality of life” are using ~45 PWh of SE. Hence with business as usual and allowing 10 billion

people the same “high-quality life” we would have to provide 450 PWh of SE. With our defined “realistic” energy efficiency measures this number decreases to 150 PWh.

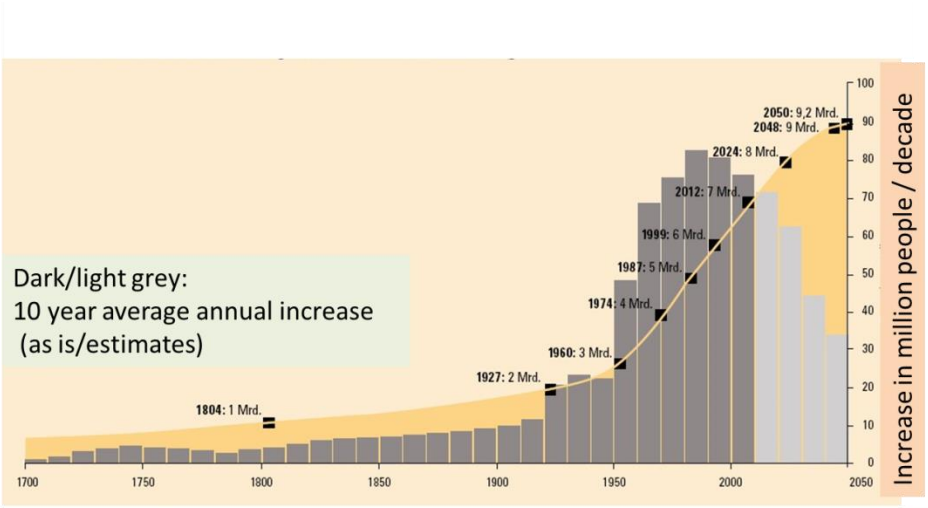

Figure 5: History and future estimate for the global population [5]

Technologies and Market Development for Renewables

Photovoltaics

One of the most fascinating and quickest developing technologies in recent years has been PV. After the discovery in the mid 1950s of the first Silicon solar cell it was first used for powering at lowest cost satellites starting in the 1960s. The replacement of small button cells in millions of calculators and other small devices by integrating cheaper small solar cells in the housing of these systems happened in the 1970/80s. This was also the time to power remote places like repeater stations with lowest cost electricity. First support mechanisms allowed the demonstration of grid connected PV systems in households (1,000 roof-top in Germany in 1990, 70,000 roof-top in Japan in 1994). It was the introduction of the best market support program ever installed, namely the feed-in tariff starting in Switzerland and Germany, where it was further optimized in 2000 with the so called “Renewable Energy Sources Act” (H.-J. Fell, H. Scheer and others) providing for all renewable technologies an individual fixed payment for each produced kWh from these systems over 20 years and allowing a fair return of investment. This catapulted the PV market from only 0.3 GW in 2000 to more than 17 GW in 2010 also because other European countries first (and more than 50 countries worldwide) adopted this support scheme. As seen in Fig.6 it was Europe which until 2011 dominated the global annual installations and created an average market growth of 50% p.a.. Unfortunately Europe experienced thereafter a strong decrease in annual

market but fortunately other regions, notably US, China and Japan (part of APAC) helped the global market to increase by 24% p.a. until 2015.

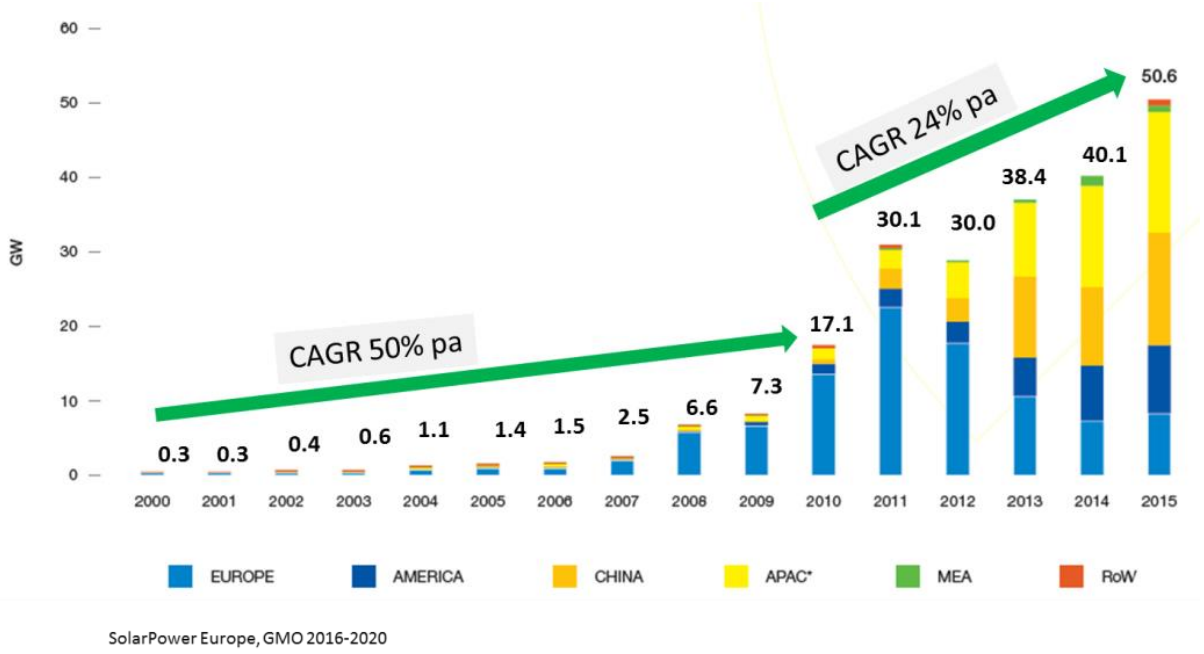

Figure 6: History of annual growth for PV market (SolarPower Europe [6])

If only an average 14% growth is assumed for the time between 2015 and 2025 the annual and cumulative PV market is shown in Fig.7. The annual market will be around 100 GW in 2020 and 200 GW in 2025. With this the cumulated market of ~250 GW in 2015 will increase to 500 GW in 2019 and approach the first TW in 2023. Major drivers for this development will be China, India, US, South America and later Africa and also Europe again.

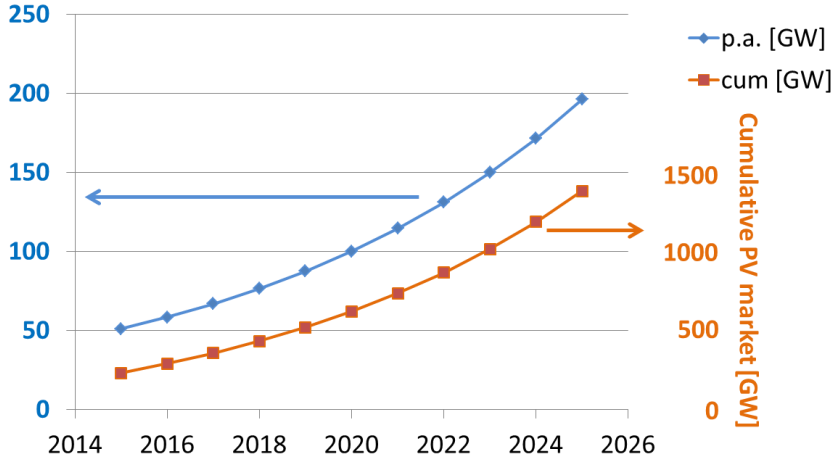

Figure 7: PV market projection in coming years

The most important driver for the market increase until today was the decrease for PV module price, which contributed in 2000 ~70% and in 2015 still ~40% to the total installed system price. The price development for a globally traded mass produced product is best

characterized by a so called Price Experience Curve (PEC) [7]. Here the logarithm of the average price is plotted versus the logarithm of the respective cumulated market volume. Typically a straight line is obtained with a product specific slope. The slope gives the decrease in price in % when the cumulative volume is doubled and is called Learning Rate or Price Experience Factor (PEF). Fig.8 shows such a graph for PV modules starting in the 1970s when at the cumulative volume of ~0.5 MW the module price was ~100$/W. 2015 we had 250 GW cumulative volume at prices ~0.5 $/W. The PEF is slightly above 20%.

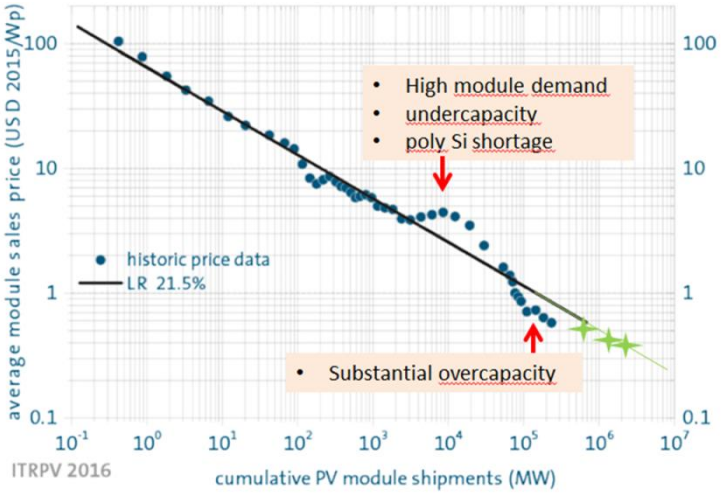

Figure 8: Price Experience Curve for PV modules (ITRPV [8])

As seen in the graph the prices followed nicely the best-fit line until a cumulative volume of ~2 GW was reached, which was around ~2005. Thereafter we had even a slight price increase and then a downturn to below the straight line. The understanding of this behavior needs no scientific explanations but a good understanding of the market mechanisms and how prices are formed. Until 2000 the small PV industry was able to obtain the poly silicon for the wafers from the scrap of the electronic industry. In 2005 was the time when all existing poly Silicon production capacities for the electronic industry were fully loaded, but with a quick market growth there was higher demand compared to production capability. As it takes a few years until complex chemical companies can be operational, the price for poly silicon skyrocketed and the price for modules increased in these times of under-capacity along the complete value chain. This was the advent of the Chinese production companies. The Chinese state government had just made the decision to heavily invest in the production of goods with high future global potential (wind energy, PV modules, batteries etc.). In only a few years Chinese companies could use ~40 billion $ investment money at very favorable conditions from the Chinese state bank to ramp up the production capacity quickly with the newest production machines from Europe and the US. In parallel many Chinese companies also went successfully public at the New York Stock Exchange and by 2010 Chinese

companies had taken over the lead in global solar cell and module production. This capacity increase even surpassed the 50% annual market growth by a factor of 2. Consequently in 2010 and later we had an overcapacity of ~100% which resulted in a dramatically price erosion as seen in Fig.8. The up-side was that many new markets could kick-start in these years but the down-side was a quick consolidation of the global production industry with heavy losses in the years 2011/12. For the future years I expect a return to the straight line as indicated by the green stars in Fig.8.

Solar power – CSP and CPV

Concentrated Solar Power (CSP)

In the mid 1980s a total capacity of ~350 MW solar parabolic trough power plants were built in the US which were seen for several years as the preferred technology for large scale centralized solar power plants. The challenge to increase the steam temperature for the turbines (increase of Carnot efficiency) could not be solved until today. As a result the production cost for a kWh from these systems are ~15 €ct/kWh, which is ~5 times higher compared to large PV plants in the same locations. One big advantage which was already demonstrated is the storage of heat during sunshine and storing for the hours after the sunset. This increases the operational time of the system and utilizes the turbines much better. Experiments are ongoing to improve the steam temperature by replacing the limiting heat exchange fluid (oil) of today.

Another possibility is the use of Dish sterling units or large Power Tower systems which receive concentrated light from 1000s of 2-axis tracking mirrors. Here the temperature is very high and a high efficiency can be obtained. First commercial systems have been built and it will be interesting to see the development of the associated cost/kWh.

Concentrated PV

Based on 40% efficient multi-junction III-V compound (GaAs) solar cells, typically used for satellite powering today, highly concentrated PV modules with a 2-axis tracking mechanism have been commercially built in recent years. The module efficiency could be demonstrated to be above 30% solar light to electricity. As with all concentrating devices they can only be used in places with high direct sunshine over the year. Similar to the CSP systems it will be interesting to see the development of the reachable cost/kWh.

Wind energy

The technology for wind mills has shown a remarkable development. The size for a single machine in the 1980s was ~75 kW with a rotor diameter of 17m and a hub height of ~25m. Today commercial systems have a power of ~7.5 MW with a rotor diameter of 126m and a

hub height up to 140m. A major drive for this development is the strong dependence of rotor diameter and average wind speed (which is for a given site higher at higher hub heights) on the power output (P):

$P \sim (\text{rotor diameter})^2$ and $P \sim (\text{average wind-speed})^3$

Parallel to this technology development the market increased from ~3.8 GW in 2000 to 51.5 GW in 2014 which gives a CAGR of 20% during this time.

Need for Storage as Solution to Variable Renewable Energies

The most important types of renewable energies, PV and wind, are by nature variable, most predictable and only a minor part with uncertainties (e.g. local clouds decreasing the PV output in those shaded areas). With today's weather satellites there is at least for the day ahead forecast high predictability. Nonetheless if we are to provide all electricity needs of a country only with renewables we must provide some storage for periods when no or too little sun and wind cannot provide the actual need. In Fig.9 the electricity load curve for Germany is shown (upper blue curve). The area below corresponds to the annual electricity consumption which is ~600 TWh. If we oversimplify assume that these 600 TWh should be produced only from PV and wind we would need ~200 GW wind and ~250 GW PV installations. The annual energy would be ~400 TWh for wind and 250 TWh for PV. With this the residual load curve (lower red dash-dotted line) is obtained which also shows that ~half of the year we produce electricity at times when it is not needed (~150 TWh) whereas the other half year we need electricity at times when there is no wind and sun (~100 TWh). The good

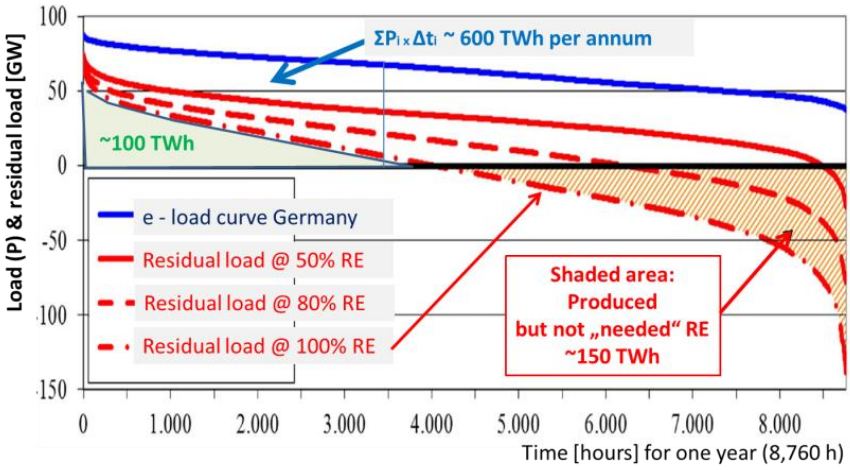

Figure 9: Electricity load curve and residual load for Germany [9]

news is that we have more electricity produced from wind and PV at times when it was not needed; hence we have energy available to account for losses associated with storage, e.g. charging/discharging batteries and conversion of electricity to hydrogen or methane.

It should be noted that the ratio between wind and PV is very much dependent on location. For Germany's load curve we have the best balance for a power ratio of ~1:1. With Germany's irradiation and wind profile this gives energy wise a ratio of ~2:1 for wind:PV (~2 kWh/W_{wind} and ~1 kWh/W_{PV}). Other regions with different load profiles and different climatic conditions may have significant differences. For example Near and Middle East regions have a pronounced load peak in summer times, much higher irradiation (~2 kWh/W_{PV}) and less wind. Therefore the ratio would be in favor of PV. In contrast we may look to Scotland with less sunshine compared to Germany but much more wind; here the ratio would be in favor of wind. Of course specific regions have also additional renewable sources which can be used to optimize the portfolio for the various renewables to reach the lowermost need for storage.

The storage of electricity has a diversity of solutions: pumped hydro, chemical batteries and also the long term storage via P2G (power to gas: hydrolysis, methane formation and, when needed, re-electrification with fuel cells). Pumped hydro is only in few countries a viable solution (Austria, Switzerland, Scandinavia) and in most others can only provide a small portion of the needed storage. Example Germany: here 7 GW are installed and in the "old times" (2006 with little PV contribution) they produced ~4 TWh electricity. Compared to the needed storage of 100 TWh this will not be a solution. Discussions to transport surplus electricity from Germany to Scandinavia have the problem that additional high voltage grids have to be built.

Most likely the solution will be a combination of various technologies. This will start with electricity storage in individual homes (several kWh with lead-acid or Li-ion batteries) where the self-consumption of PV can be increased significantly from ~20% up to 80% (especially when an e-car is also present). In a municipality there is still surplus electricity which can be collected and stored in MWh batteries (e.g. NaS, redox-flow batteries). Several municipalities may run jointly a P2G unit for the rest of long-term storage needs.

It is interesting to analyze the potential of price decrease for kWh storage in homes and SME's. For this it is useful to construct a Price Experience Curve for the Li-ion battery cells, the most costly part of such a storage unit. The result is shown in Fig.10 for automotive kWh-units which has a Price Experience Factor of ~15%, i.e. each doubling of the cumulative volume of sold battery cells will decrease the price by ~15%. At the time the curve was made

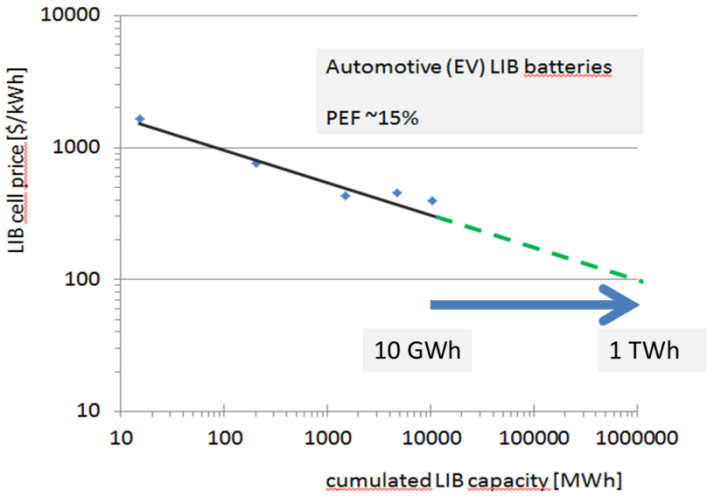

Figure 10: Price Experience Curve for Li-ion batteries [10]

we had a cumulative volume at the end of 2013 of ~10 GWh of sold Li-ion battery cells with a price of ~350 €/kWh. The interesting question is: when could we expect a cell price of 100 €/kWh? For this we extrapolate the straight line and obtain at ~1 TWh cumulated capacity this envisaged price. The next question is: at which time would we like to have this cumulative volume reached, bearing in mind that a meaningful growth rate should be in place. If we assume that in 2030 we would like this price, we can calculate the necessary growth rate, which is 31 % p.a.. This may seem ambitious but if we compare this with the growth rate for the cumulated PV modules in the time 2000 and 2010 the industry was capable to demonstrate 41%. So this is a realistic goal to be reached.

To complete a battery we must add the assembly cost which is shown for the years until 2030 in Fig.11. The assumptions for a simplified calculation to obtain the storage cost in €ct/kWh are as follows:

- Lifetime of battery 5,000 cycles
- Finance cost ~same as investment
- Usable capacity per cycle ~80%
- → cost per kWh = (Invest x 2)/(5,000 x 0.8)

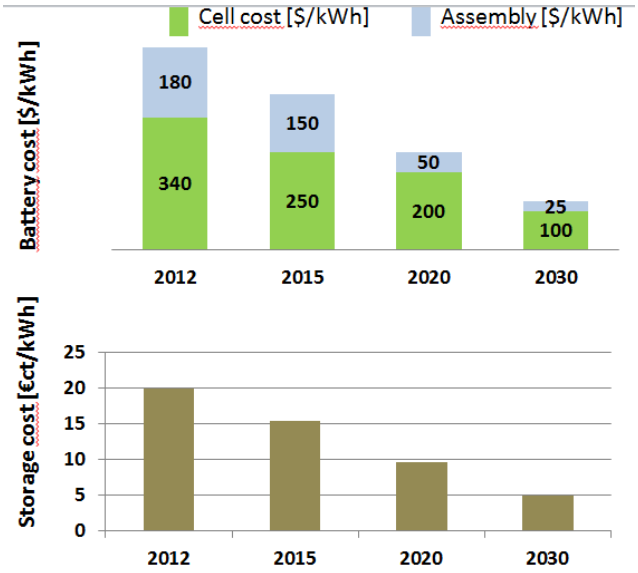

Figure 11: Development for Li-ion battery prices and storage cost

The storage cost is expected to decrease from ~ 15 €ct/kWh today down to ~5 €ct/kWh in 2030. Even if we have to add some electronic hardware for the stationary house storage we have a very favorable price for a stored kWh of PV electricity when compared to a purchased kWh from the utility. This price development gives also very good prospect for future e-cars. If we assume a petrol driven car with 5l/100 km the cost is 7.5 € at 1.5 €/l. An e-car using 15 kWh/100 km has a cost of only (1.5 – 2.2) € which is 3-5 times less (PV (5-10)€ct/kWh in southern and northern regions, storage cost 5 €ct/kWh).

The ~100% Renewably Powered World

The energy picture for a fair for all and renewably powered world assuming realistic energy efficiency measures of a factor 3 is shown in Fig.12. Important to note is that primary energy equals SE, electricity makes up 2/3 of SE (100 PWh) and total losses to convert SE into EE are only 1/3 of SE. This is obviously very different to the situation as of today (compare with Fig.1) and results in the ratio PE : SE : EE = 1.5 : 1.5 : 1.

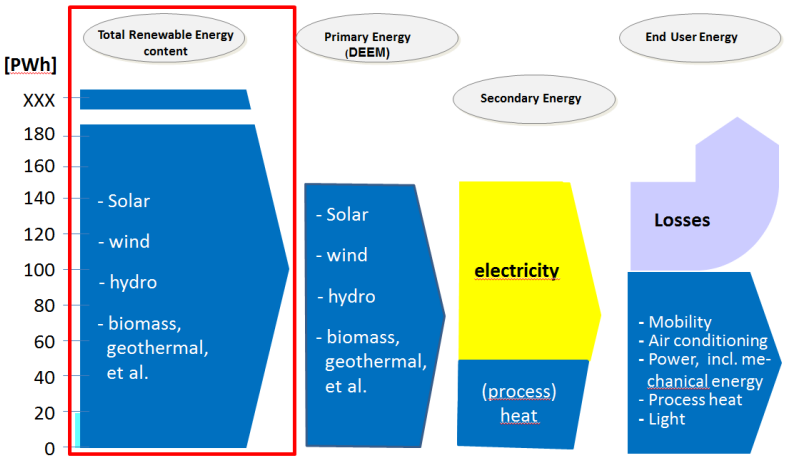

Figure 12: Energy picture for a fair and 100% renewably powered world

When it comes to the needed portfolio of the different renewable sources it is important to understand what the respective technical and – even more important – the sustainable potential is. A comprehensive review for this topic was done in a detailed publication [11] and is shown in Fig.13. The technical potential summarizes all land based areas (and near coastal areas for off-shore wind) which would technically allow the utilization for a given renewable source. In contrast, the sustainable potential, which is only ~4% of the technical one, takes into account important ecological, economical and environmental aspects to be fulfilled. Fortunately the 150 PWh annual needs are only ~5% of the sustainable potential – hence there is no obvious or unsurmountable hurdle to have the needs covered only by renewables. Also important is the fraction for solar, wind and all others (including hydro, geothermal, biomass etc.) of the sustainable potential which is 90%, 9% and only 1%, respectively.

	Technical potential [PWh/year]	Sustainable potential [PWh/year]	
Biomass	224	28.0	
Geother	202	6.2	~1%
Hydro	45	3.4	
Solar	78,400	2,800.0	~90%
Wind	476	280 .0	~9%
total	79,347	3,117.6	100%

Figure 13: Technical and sustainable potential for various renewable technologies [13]

In order to account for local opportunities especially for “all others” we should increase the share for our 150 PWh from 1% up to ~20% which would imply that 30 PWh should come from these sources. Some thoughts why this is not likely to increase significantly:

- *Hydropower*
  The last 50 years had an almost linear increase of ~0.5 PWh per decade to3.5 PWh today. Even if we assume the same capacity addition – which becomes more difficult in the future – we arrive in 50 years at a cumulative capacity of ~6 PWh.
- *Geothermal*
  There are limited places with high surface temperature. This and the low Carnot efficiency resulting in a high specific electricity generating cost make it unlikely that a major portion to the 30 PWh will be contributed. From today’s installed capacity of ~15 GW, producing ~0.09 PWh there is even with the globally available capacity potential of ~200 GW an annual electricity production of ~1.2 PWh possible [12]. Even if we double this number, not more than 2 – 3 PWh will be produced from this technology.
- *Bioenergy*
  If biogas is produced with the fastest growing plants and electricity made with a 40% power station there is only ~20 MWh/ha electricity p.a.. Compared with PV in the sun-belt 80 times electricity on the same area is produced, in northern countries like Germany it is still 40 times more.
  For biodiesel the situation is even worse: while on an area of 10 m² with plants for biodiesel a diesel fuelled car can only drive 110 km (5l/100 km), an e-car can drive with PV generated electricity on the same area as far as 10,000 or 20,000 km p.a. for northern areas and sun-belt regions, respectively.
  Nonetheless we have substantial amounts of bio-waste which should be used in the best possible way, also to produce electricity – but a major portion of the 30 PWh are difficult to imagine.
- *Ocean energy (wave and tidal)*
  Although the theoretical energy production from these sources is huge there are severe practical limitations for harnessing cost efficiently this energy resource. Some favoured areas may well be used for this technology but again it is difficult to see a big part for the 30 PWh coming from here.

For wind there is also good reason to increase the relative 9% towards ~20% from our needed SE. Major reasons for this is:

- Wind and solar are balancing very well
- Wind on-shore is cost effective and has a good capacity factor (2-3 kWh/$W_{\text{wind inst}}$)

- Wind off-shore has an excellent capacity factor (3-5 kWh/$W_{wind\ inst}$) and shows good prospect of low cost (just recently a PPA was awarded to Vattenfall at <5€ct/kWh)
- From today's installed capacity of ~420 GW in 2015 the annual growth can be smaller than 10% p.a. to reach the 30 PWh electricity production

For solar we will decrease the relative fraction from 90% down to 60% for our 150 PWh scenario. Three technologies should contribute in this area: (a) solar PV (decentralized), (b) solar power centralized and (c) solar thermal (process) heat.

- *Solar PV (decentralized)*
  The development of this fascinating technology was described in the preceding section. The annex "decentralized" should cover all PV systems from the small W-range (pico-PV) via the kW-installations (roof-top for houses) up to the MW-range (commercial roof-tops, community owned green-fields). The question is whether we can reasonably assume that these systems are able to grow in order to be able to supply for example 30 PWh of electricity let us say around 2050. Fig.14 illustrates a quick exercise for such a growth: Coming from the past 2 decades with a proven CAGR of 20 and 50% p.a. and as shown earlier that the running decade is realistic to demonstrate 20% we only need much lower GAGR's for the coming 3 decades to reach a cumulated capacity of 23 TW for such PV installations. If we take a conservative average number of only 1.3 kWh/$W_{PV\ inst}$ these PV systems would produce in 2050 about 30 PWh electricity.

	V 1	V 2
Decade	% growth	p.a.
1990 - 2000	*20*	*20*
2000 - 2010	*50*	*50*
2010 - 2020	20	20
2020 - 2030	14	15
2030 – 2040	8	10
2040 – 2050	4	5
cumulative PV power in 2050 [TW]	**23**	**30**
Annually produced energy [PWh] in 2050 at 1.3 kWh/W (average)	**30**	**38**

Figure 14: Necessary growth rates (simplified) to provide 20% PV for the future 150 PWh of SE

Of course this simple approach does not take into account dismounting old installations after ~30 years and would assume an unrealistic stop of installations in 2051 with a gradual increase again as in the years 2010 to 2015. More realistic is a logistic growth curve to reach

asymptotically the 23 TW as shown in Fig.15 [13]. Here the increase for PV systems is shown for the major regions worldwide with adjusting the respective growth to the local situation and the relative share is taken in proportion of the expected population [5] in the various regions.

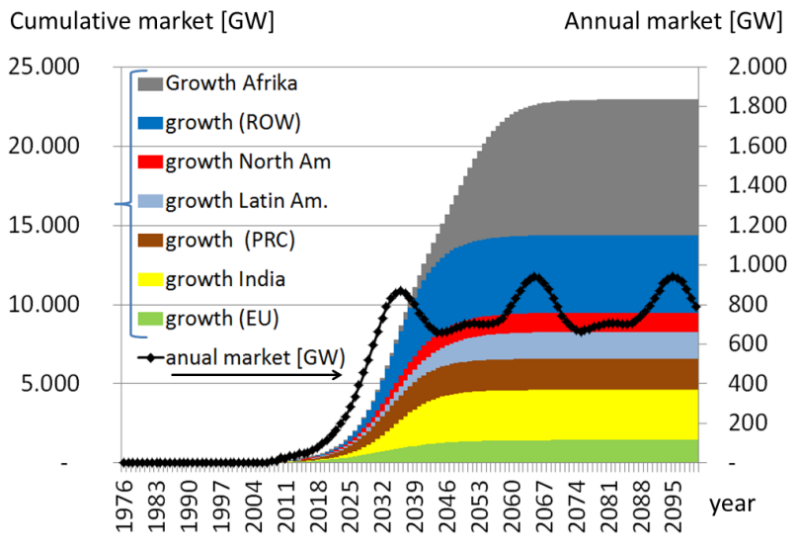

Figure 15: Logistic growth curve to reach the 23 TW PV installations (= ~30 PWh electricity p.a.)

In order to arrive at the cumulative capacity, the annual market growth is shown as a black dotted line (right ordinate). The peaks and valleys derive from the assumption of an average lifetime of the PV systems of 30 years. In the steady state after ~2040 the annual installations are in the range of ~800 GW per year (+/- 100). From our today's ~70 GW in 2016 we have still a way to go but as we have neither material limitations nor manufacturing bottlenecks this ambitious goal could be well reached, given the track record of the last decade.

There is another very important point why this PV growth will really happen. If the increasing PV installations could only be achieved with subsidies and support against less expensive alternatives, I would not dare to make such projections. However, with recently published power purchase agreements (PPA's) for new nuclear power stations and new PV systems, we are now able to compare the price for electricity for the alternatives in a fair way.

For new nuclear we refer to the agreed contract (still not started) between Great-Britain and France to build two Areva EPR 1,600 MW nuclear reactors with a planned investment of 26.5 bn €. EdF will only build these reactors if GB accepts a guaranteed price for each produced kWh with the following conditions: (a) 92.5 BP/MWh =~12 €ct/kWh, (b) duration 35 years after start of operation, (c) adjustment according to inflation, starting with the reference year 2012, (d) expected completion 9.5 years after start of work. With these numbers the price to

be paid (in today's currency) is calculated and shown in Fig.16 for two inflation rates assumed (1 and 2.5% p.a.) and an expected start of operation in 2027 (earliest start in 2017 plus 9.5 years). Although inflation rates were rather low in recent years, it is expected that in the long run an average inflation rate will be around 2%. With this the first kWh in 2027 has a price of ~16 €ct/kWh and will increase towards ~35 €ct/kWh at the end of the 35 years. The average or "effective" price for this new nuclear power is ~25 €ct/kWh.

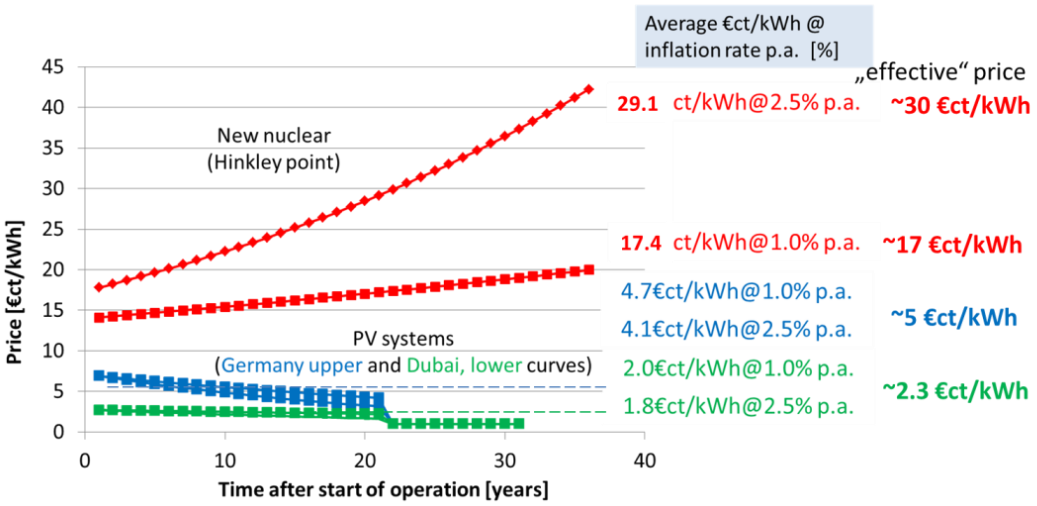

Figure 16: Price development for new nuclear (Great Britain) and new PV (in Germany and Dubai) based on existing ppa's (power purchase agreements)

In contrast to this agreement there have been several PPA's for new PV MW-sized green-fields recently signed. In several calls for tender in Germany for green-field PV plants with a size of ~100 MW, the contracts were awarded (a) at and below 7 €ct/kWh guaranteed price, (b) duration 20 years, (c) no adjustment with inflation and (d) expected completion ~1 year. Another PPA was signed recently by Dubai Electricity and Water Authority (DEWA) and Abu Dabi Future Energy Company (Masdar) for a solar park at 2.99 $ct/kWh with similar boundary conditions as in Germany. Another ppa was signed in Chile at 2.91 $ct/kWh. The lower PPA in Dubai and Chile reflect the differences of irradiation for Germany (~1 kWh/W_{PV}), Dubai (~1.9 kWh/W_{PV}) and Chile (~2.3 kWh/W_{PV}). In the case of PV we can realistically assume a lifetime of ~30 years. If we conservatively take ~1 €ct/kWh for maintenance and repair for the 3rd decade for those PV systems we can calculate the "effective" price for the PV systems in Germany as follows: two decades with ~7 €ct/kWh and one decade with 1 €ct/kWh → "effective" price = (2 x 7 + 1) / 3 = 5 €ct/kWh. Similarly in Dubai and Chile the "effective" price is ~2.3 €ct/kWh. This calculation is based from the point of view of an user for these systems; an investor running the systems should remember that for the above mentioned PV PPA's he will receive the price after inflation as shown in Fig.16.

In summary we have already today the situation that with current prices a PV kWh in less sunny Germany is 5 times cheaper compared to a new nuclear power station. This factor increases in sunnier regions like South America and Middle East to more than 10. Whenever the financial world has understood this interesting result the 100s of billions of € investment money will no longer go into new nuclear but in new PV (and wind, see above PPA for wind). There is no longer any meaningful reason why a country should decide for new nuclear. Similar arguments are with clean coal (CCS, carbon sequestration and storage) as this will add cost and make a clean fossil kWh also very expensive at above 10 €ct/kWh.

Until a mandatory CCS will be in place there may be due to the Paris agreement a possible move to a reasonable Carbon price. This started in Europe some years ago with ~30 €/t-CO_2 and collapsed to ~5 today for various unfortunate reasons. With the goal to keep temperature increase well below 2°C we may anticipate that a price of 50 €/t-CO_2 may become realistic. This would add a cost to fossil power plants of ~6 €ct/kWh for lignite, ~5 €ct/kWh for hard coal and 2.2 €ct/kWh for gas – plus running the power plant and buying fuel – for sure more expensive than new renewables as demonstrated before.

- *Solar power centralized*

  While PV (and wind) systems up to the multi MW-range are well suited to cover the energy needs regionally for private homes, SME's, hotels and offices, the question remains how to provide the necessary energy for the large and energy intensive industry. There has always been a tendency to move such industries to regions with low energy costs, which in the past was predominantly in areas with hydropower. Examples are metallurgical silicon plants in Scandinavia and Aluminum production from bauxite in Iceland. For all those countries lacking hydropower a great opportunity could arise to keep or attract the industrial location of such energy intensive industries in their region if they have good solar (or wind) potentials. Regions around the Mediterranean area, desert regions like Gobi in China, Sahara in Africa, Atacama in Chile, large areas in Australia and many more could provide multi TW power stations for lowest price electricity and heat. First TW-PV plants are already built in China and many more could use either huge standard PV plants (fixed plate), concentrated PV (2-axis tracking systems with 500x concentration using multi band-gap GaAs solar cells) and / or concentrated solar power (parabolic trough, solar dish or power tower, which can provide not only electricity but also process heat for industry).

  A quick exercise shows that with such large centralized systems an energy of 10 PWh in 40 years can be provided with reasonable growth rates: If we assume an average size 2 TW we need an annual growth of ~22% p.a., i.e. in the next 10 years

7 of such systems should be built. Looking to the plans in India, Africa, Middle East and China for similar large scale systems this seems realistic. Combining the various technologies there is a good chance to reach in the coming decades an annual energy production of ~30 PWh.

- *Solar thermal (process) heat*
  At the end of 2010 we had globally ~270 million m² cumulative solar thermal installations, with more than 70% installed in China. This corresponds to ~190 $GW_{thermal}$ and an energy equivalent of ~130 TWh. While most of these installations are used to cover the low temperature heat for warm water it is increasingly used also for district heating (example Denmark).
  An additional business opportunity for thermal systems will arise which is medium temperature process heat for many industrial applications from SME's up to big companies. Whether the annual global energy needs for this technology segment will approach 30 PWh remains to be seen; it all depends on how the customer needs can be satisfied most efficiently in comparison with electricity based solutions from a cost and convenience point of view.

In summary we have for the portfolio of renewables to cover the future SE needs of 150 PWh the following picture:

- Solar PV (decentralized) ~20% = 30 PWh
- Solar power centralized ~20% = 30 PWh
- Solar thermal (process) heat ~20% = 30 PWh
- Wind energy ~20% = 30 PWh
- All other ~20% = 30 PWh
- Total 100% = 150 PWh

The above split should only emphasize the relative importance for all renewables and not be taken as a quantitative forecast for 2050. It could well be that Solar PV becomes bigger and Solar power and/or Solar thermal smaller. But this does not change the basic message from this exercise: namely that renewables will for economic and environmental reasons take over the global energy supply in the coming decades from today's fossil and nuclear technologies.

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