PV AS ONE OF THE MAJOR CONTRIBUTORS TO A FUTURE 100% RENEWABLY POWERED WORLD – IMPORTANCE AND EVIDENCE FOR COST EFFECTIVE ELECTRICITY STORAGE

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ABSTRACT: Based on today's energy carriers and user characteristics a 100% coverage with renewable energy technologies can be accomplished in the middle of this century facilitated with appropriate energy efficiency measures as analyzed in more detail in a recent publication [1]. As the most important renewable technologies will be PV, wind and solar concentrating devices the relative share of electricity for future secondary energy will increase considerably from today's 20% towards more than 60%. In order to balance the variable renewable technologies with the needed power load it becomes increasingly important – beside locally optimized portfolios of the various renewable technologies and Demand Side Management – to introduce cost efficient storage devices. Evidence for cost efficient battery storage in the kWh range is shown for Li-Ion batteries, first by demonstrating that the price decrease for these batteries follow a Price Experience Curve (PEC) until today and second that by using reasonable growth numbers favorable prices will develop in the 2020s facilitating e-cars and storage for home owners. Adding larger storage capacities at the municipality level will then minimize the need for extensive and expensive transmission grid enlargement.

Keywords: 100% renewable energy, battery storage, energy efficiency, PV (Photovoltaic), wind, solar concentrating devices (CPV and CSP), solar thermal, PEC (Price Experience Curve), PEF (Price Experience Factor), LCOE (Levelized Cost of Electricity)

1 INTRODUCTION

Until only a few years ago it was widely believed that although renewable energies may increase their share in the future energy portfolio, however, with only a minor contribution. This has by now drastically changed. While for example the International Energy Agency (IEA) did not see a significant contribution from renewables in their earlier regularly published World Energy Outlook (WEO) [2] this is qualitatively different in the latest editions, especially in dedicated sections like the recently published "hiRen scenario" [3]. For example, PV is seen as the lowest cost technology by 2050 among the various electricity generating technologies with a significant share in the electricity sector. Energy projections from major oil companies [4, 5] also see the increase in their future energy projections mainly coming from renewables – while keeping the current contribution from fossil fairly constant.

There is widespread consensus about the importance for the implementation of energy efficient technologies to power the end energy needs; this, however, not by decreasing the living comfort, but by having the same quality of life with much less energy, or by using renewable technologies to even have a better quality of life due to their superior environmental footprint. Even with conservative assumptions it is possible to reach a needed yet reasonable secondary energy for all energy needs, which will be mainly electricity but also energy for heating and cooling purposes as well as process heat for the industry. A major assumption will be the change within the transportation sector from oil to electricity, either for direct use or, after transforming renewably produced electricity with the concept of "power to gas", with hydrogen or methane (or derivatives).

With appropriate market support mechanisms for the various renewables, notably the Feed-in tariff (FiT) starting in Germany and Switzerland in the 1990s and the EEG (Renewable Sources Act) in 2000, it was possible to substantially decrease the generation cost in particular for wind and photovoltaics due to the induced volume increase. The specific prices per power unit for the various renewables are following individual price experience curves (PEC), in analogy to well-known consumer products like semiconductor chips or flat panel displays [6].

2 CURRENT PRIMARY AND SECONDARY ENERGY SITUATION

The current situation for the primary, secondary and end energy is best described with the energy unit PWh (Peta-Watt-hour), which is 10^{15} Wh (or 1,000 billion kWh). The change from primary energy (~140 PWh) to secondary energy (~90 PWh) into the actually needed end energy (~40 PWh) is associated with considerable losses. Most losses within the first transformation are due to the low average efficiency (~33% on a global level) to produce the ~20 PWh electricity. The substantial losses for the second transformation into end energy are due to many low efficiency products (like light bulbs, inefficient gasoline and diesel driven cars and many others) and there is also unnecessary energy usage (like warming and cooling of insufficiently isolated houses).

Today's split between the major primary energy sources can be simplified as roughly ¼ each for oil (mainly transport), coal, gas as well as nuclear and renewables (with renewables about double of nuclear). The break-down of the secondary energy into the most important sectors, again in simplified numbers, is approximately ¼ each for transport, for heating and cooling of houses, for process heat and power for industry (without electricity) and the remaining for electricity (both for industry and all others).

The burning of fossil fuels, both for electricity production, heating needs for houses as well as for transportation results in a considerable increase of CO_2 in the atmosphere, one of the major constituents of anthropogenic climate changing Greenhouse Gases. In its recent report from the IPCC [7] even more evidence has been presented with regard to an unacceptable rise in CO_2 concentration associated with global temperature rise. There is scientifically consensus that the quick and high CO_2 increase, which did not happen in the last some million years before, will most probably result in a high temperature increase which should not be tolerated by educated people. The money needed to repair the damage caused by the described effects will be considerably more over the next decades compared to the investment needed to quickly change the energy picture from traditional to renewable technologies [8]. Hence such a change would not only be viable from a technological and environmental, but – at least equally important - from an economical perspective.

Considerable efforts have been undertaken to find technical solutions to sequestrate CO_2 in power stations and to store it forever in a suitable way (deep sea storage, empty natural gas caverns). Unfortunately this CSS process (Carbon Sequestration and Storage) decreases the efficiency of the power station and adds significantly to the cost. A clean coal kWh electricity is expected to be in the range of ~13 $ct. This is more compared with today's electricity generating cost of photovoltaics and wind. Today's magic discussion with shale gas does not really change this picture: although a gas powered station emits only half CO_2 compared with coal fired ones there is nonetheless the need to also sequestrate CO_2 with similar cost as described before. During the transition phase towards 100% renewables it is of course desirable to change as quickly as possible all coal fired power stations to gas powered ones in order to minimize the accumulation of CO_2 in the atmosphere and to optimize the balancing of the load curve together with variable renewable energy sources like wind and solar.

Nuclear fission was expected in the 1950/60s to power the world's energy needs at lowest cost. This picture has changed dramatically: in a recently signed LOI (letter of intent) between the British and French energy authorities it was agreed to pay for each produced kWh electricity in two new nuclear power stations (Hinkley Point C with 1,6 GW each) a price of more than 12 $ct for a period of 35 years including inflation adjustment. If we conservatively assume an inflation rate of only 2.5% per year we arrive at a price of about 30 $ct/kWh at the end of the payment period! Even if there were no problems with outreach of uranium, safety issues, inappropriate insurance and open questions with waste storage, the before mentioned cost situation alone rules nuclear fission out as a future option.

The world today distributes the energy resources in a very unfair way: a few years ago approximately ¼ of the global population (~1.5 bn people) consumed ¾ of primary and secondary energy (~105 and 67.5 PWh, respectively). From this it can be calculated that with our "High Quality" living standard one billion people today need 70 and 45 PWh for primary and secondary energy, respectively.

3 FUTURE SECONDARY ENERGY NEEDS AND IMPORTANCE OF EFFICIENCY INCREASE

Following the projections of the United Nations on future development of the global population [9] and taking their medium growth model there is good evidence for the assumption that we may have a leveling for the global population at ~10 billion people. Allowing everyone to have the same "High Quality" of life as described before and assuming today's mix of primary energy sources we would need 700 and 450 PWh for primary and secondary energy, respectively.

It is well recognized that energy efficiency measures could change this picture very positively to the better and this by keeping nonetheless today's quality of life. There are two important screws how to decrease the needed end energy: (1) active measures like using more efficient light bulbs or electric mobility and (2) passive measures which help to no longer need energy for the anticipated "High Quality" of life, like isolation of buildings to drastically reduce the energy for air conditioning or future smart cities with integrated transportation concepts to decrease the needed energy for mobility.

3.1. Active efficiency measures

Let us elaborate on two examples for active measures: if we not only in Europe but worldwide exchanged all traditional light bulbs, which only convert less than 10% of electric power into the needed light intensity (measured in lumen), by (O)LED's ((Organic) Light Emitting Diodes) which convert more than 60% electric power into lumen we could significantly decrease today's annual electricity consumption for lighting. Already today we have for many street lighting high pressure Na-lamps and many office buildings with fluorescent tubes which have a higher conversion efficiency than light bulbs but lower than LED's. We could therefore decrease the needed electricity from today's 2.1 PWh electricity easily by a factor of two when we only partially exchange all non-LED lamps but more aggressively also a factor of four by exchanging all. Many people challenge the change from traditional light bulbs to LED's by arguing that the price for the latter are much more expensive for the same provided lumen. Here we have to train all people that the initial investment alone does not give the correct answer concerning competitiveness but rather a "total cost of service" or "Levelized Cost of Service (LCOS)" over the lifetime must be calculated. It is this same principle not only to compare the initial investment for a needed service but to compare the specific cost of service calculated from the overall lifetime of the given alternatives (like the electricity cost (LCOE) from PV and wind compared to the one from traditional fossil and nuclear power stations).

The second example concerns the change from traditional oil based to mainly electricity powered transportation. A very important feature of electric vehicles is the much higher efficiency which is about 60%, compared to a diesel engine which delivers only up to 30% of the secondary energy diesel fuel to the motion of the car. It should also be noted that today most transportation for private cars, trucks, buses, ships and planes is powered by petrol – with the exception of railways which run on electricity in many countries. This will change in the future and as in the case of long range trucks, ships and planes, electricity will not be the fuel of choice. Instead, these vehicles will be powered in the future either through biofuel or "power to gas (P2G)". The latter is obtained through hydrogen produced by water electrolysis (with renewable electricity) which reacts with CO_2 to obtain CH_4. In the case of trucks and ships the use of hydrogen (or gas with a reformer, which splits hydrogen from the used gas) is also possible, if a suitable infrastructure is envisaged.

It is well known that most of the private cars drive less than 100 km per day, which is a distance easily covered even by today's electric cars. I can see an easy adoption for electric cars in areas where families have a second car which is often hardly used for distances above this range. Even when the first car travels less than the mentioned 100 km per day on most days, it is desirable to have the possibility of driving longer distances on some days. This could be done in a variety of ways: one could use cars which are already available today e.g. from Tesla, Opel (the Ampera) or BMW (i3). Alternatively, one could also use hydrogen either in a combustion machine or in combination with a small fuel cell producing electricity to recharge the battery. The latter would be perfect if we consider this fuel cell as a power source in houses (or districts) at times when there is no sun and wind and installed batteries are empty.

3.2. Passive energy efficiency measures

In many countries a major part of primary energy is used to provide the heating and cooling of buildings. For the example of Germany, this amounts to approximately 40%. Hence, a relatively large amount of money is spent by individuals to buy gas and oil for heating and cooling purposes. Obviously, this is an area where we could drastically decrease the amount of energy used today.

Technologically, this topic is one of the easiest, but in reality it is one of the biggest challenges to overcome. The easiest way to make the best use of a roof for solar capturing is the orientation of houses with one roof facing south. All that needs to be done is a proper orientation of the roads and guidance on how to orient one roof towards the south. It would be a major achievement if we could all agree on such simple measures which do not cost additional money – they just have to be planned properly!

While new houses now have all the possibilities to include proper insulation at a reasonable price, the installation of the different electrical wiring and piping for cold and hot water is necessary, too. This is very different for existing houses, which only undergo major renovations at a rate of about 1% to 2% per year, during which new state of the art features can be implemented at a reasonable price.

A good way to push for implementing state of the art technology in new buildings is the new European directive which gradually gives a mandatory goal for proper insulation in the first place and goes further into a future house, which produces more energy than it consumes over the course of a year. This will consequently start with passive measures like insulation but will increasingly include the production of electricity and heat at the point of its use, which is perfectly well provided by decentralized PV systems and thermal collectors on the individual houses. It should also be highlighted that the insulation of houses alone is not enough for the well-being for the residents: in order to prohibit the growth of mold fungus if the house is not carefully ventilated (…and most people are just too lazy), a well-functioning forced ventilation must also be installed. It will still require a lot of work for a standard package at a reasonable price to be available for existing houses.

3.3. Today's simplified secondary energy picture with "mild" efficiency measures

Based on the few examples discussed before and making simplified assumptions for the various energy sectors the decrease for the energy needs can be summarized by: ~-40% for mobility, ~-80% for low temperature heat, ~-20% for the rest of the industry and ~-40% for electricity in industry as well as for the rest of the electricity consumption. The original secondary fossil fuel for transportation is assumed to shift completely to electricity or hydrogen/fuel derived from renewable electricity (in the latter case we have to provide a small additional fraction of electricity corresponding to the associated losses). The total secondary energy of today would shrink from 90 PWh to approximately half of that (45 PWh). In relative terms the share of total electricity would increase towards 54% of secondary energy, low temperature heat would decrease to 11% and process heat for industry and SMEs would be at 35%. This factor of 2 in energy efficiency may be called "mild" efficiency measures. If we follow the same pattern for a fair energy distribution for the future 10 billion people and keep the same split between renewable and traditional energy providers, we would need 350 and 225 PWh for primary and secondary energy needs, respectively.

3.4. Tomorrows realistic secondary energy needs in between mild and aggressive efficiency measures

Considering only renewable technologies to power the needed secondary energy needs in the future it is no longer necessary to care about primary energy and associated losses which occur when transforming exhaustible primary energy (like fossil and nuclear) into secondary energy.

In comparison to the "mild" efficiency improvement a much more ambitious goal has been elaborated by von Weizsäcker and colleagues [10, 11]. While the first book described the way for a four-fold efficiency increase, they concluded in their latest book even a five-fold increase in efficiency. The latter would result in a secondary energy need – again allowing all 10 billion people a similar energy use – of only 90 PWh. A similar secondary energy scenario was elaborated by WBGU [12], where 90 PWh were anticipated for 2100 and also by Greenpeace for the year 2050 [13].

With a simplifying but realistic assumption that the mild scenario (225 PWh) can be improved and the most aggressive one (90 PWh) may not be easily reached on a global scale, we take 150 PWh as a good working hypothesis being in the middle of the two extremes. This more realistic number is also supported by some more elaborated future projections given by IEA [14]. As already seen in the mild scenario where the relative fraction of electricity increased from today's 22% towards 54% there will be a further increase for the proposed 150 PWh scenario. For simplistic reasons a fraction of 2/3 electricity is taken for the later discussion. It should be noted that this increase is much higher compared to many other studies which is mainly caused by our assumption that all transportation is provided by electricity (or fuel made from renewably produced electricity).

4 STATUS AND PROSPECT OF THE MAJOR RENEWABLE ENERGIES

4.1. Wind power

Although wind power is one of the oldest technologies used by mankind to power machines it is only recently that with modern wind converters an increasing fraction of electricity is produced. The increase of globally installed cumulative wind power came from 6.1 GW in 1996 to 17.4 GW in 2000 up to 318 GW in 2013 with a CAGR (compound average growth rate) of 25% per annum between 2000 and 2013 [15]. Using a simplified global average of 2.5 kWh/ $W_{wind\ installed}$ a rough estimate gives ~800 TWh/year electricity worldwide produced from all installed wind mills in 2013. Sadly, 2013 was the first year since 1996 which showed a decrease in global installations compared to the year before: 35 GW in 2013 and 45 GW in 2012.

Understanding the physics of a modern wind mill answers easily the reason for the ever higher pylons and longer blades. The power output of a windmill increases with the 3rd power of wind speed; as the wind speed is increasing with the distance above ground (quickly above sea level, slowly above ground and even more slowly in towns and forests) it is important to have the rotors as high as possible. Pylons are approaching today up to 150 m. Having high pylons it facilitates the usage of increased rotor diameter. As the power output of a windmill increases with the square of the rotor diameter this again helps a lot to decrease further the electricity generating cost. Today blade lengths above 80 m have been demonstrated and the goal is to achieve soon 90 m (which would make a 180 m rotor diameter).

In addition to windmills on-shore, which typically have an equivalent of 1,500 to 3,000 full load hours per year, great efforts are being undertaken worldwide to use wind mills also off-shore. Not only do we have high wind speeds at reasonable heights above sea level but in addition there is a significant increase in the full load hours towards 3,000 and up to more than 4,000 hours per year. However, the harsh conditions in the maritime environment both for installation and long term running add today significantly to the electricity generating cost (LCOE).

4.2. Solar thermal for heating and cooling

Today two types of solar thermal collectors have emerged, flat plate and tube collectors. The global market with an annual installation in 2010 of ~60 million m^2 (corresponding to ~40 GW_{th}) resulted in a cumulative market of ~270 million m^2 (corresponding to ~190 GW_{th}). The countries with most installations are China (194 million m^2), EU27 (22 million m^2), Turkey (21 million m^2) and all other countries below 10 million m^2.

Most solar thermal systems are used for producing domestic hot water for direct use and also for heating purposes. With new technologies, both closed (thermally driven sorption chillers) and open cycles (desiccant evaporative cooling systems) it is also possible to use solar thermal power to produce cold (and/or dehumidification). Today's electricity peaks during summer and midday in southern regions could be drastically reduced due to less electrically powered air conditioning systems.

The temperature range for thermal collectors is in the range 100 to 200°C. The lower range is used for the domestic hot water heating and the higher range can be utilized for provision of medium process heat for industrial use. Some countries, notably Denmark, have also introduced district heating with solar thermal systems in many municipalities.

While in the longer term the application for domestic hot water and heating may not grow so much because of efficient insulation for future houses it will be all other applications which will need a big growth for this sector.

4.3. Solar thermal for electricity production (Concentrated Solar Power, CSP)

The first parabolic trough system was built in 1912 in Al Maedi near Cairo, Egypt and started operation in 1913. It consisted of five parabolic concentrating reflectors, each 62m in length and 4m in width, oriented in north-south direction together with a mechanical tracker system which kept the mirrors oriented towards the sun throughout the day.

It was until 1990 when in California (US) a series of parabolic trough "Solar Electricity Generating Systems" (SEGS) was built. With each new generation in only a few years there was considerable technological improvement with accompanying decrease of generation cost for electricity. Unfortunately the momentum was stopped when Luz International Inc., the company which built these systems, filed for bankruptcy in 1991. This was mainly caused by a change in the federal and state tax credit schemes and a drop in oil and gas prices at that time. Nonetheless these systems are still today producing electricity.

A new generation of CSP systems based on parabolic trough started when in some countries like Spain market support in form of feed-in tariff systems was started. The technology development concentrated on the optimization of the receiver and the mirror system to concentrate the sunlight. While for the first the company SCHOTT has an almost perfect product with very high absorption, low losses and introduction of special glass where the expansion coefficient for the outer glass tube meets the inner metal tube at each interconnection point. The latter point was in earlier projects a problem because of breakage of the glass attached to the metal due to the daily high temperature fluctuations. Today's parabolic trough systems use oil as heat fluid which is the limiting factor for the temperature being around 400°C. This of course limits the efficiency in the subsequent turbine where electricity is produced. Unfortunately there is no further price decrease for the generators and this is the reason why today the electricity generation cost is in the range of 16 €ct/kWh, more than twice as much as for PV systems in similar locations. There is still one benefit which is the possibility to store the heat throughout the day in a molten salt tank which can be used after dawn to drive the generator. New developments with first pilot projects aim to increase the temperature by using molten salt within the absorber, which will result in significant efficiency increase and thereby considerably decrease the generation cost of electricity.

Another technology, the use of many heliostats to concentrate sunlight onto a single absorber on top of a tower, is also used in a number of projects. Here the temperature is very high able to provide process heat for special chemical reactions or to be used in turbines with high efficiency.

4.4. Photovoltaics

The most fascinating technology to produce electricity is the use of Photovoltaic solar cells and modules. Sunlight (direct and diffuse) is absorbed in a solar cell which consists of a layer or wafer of semiconductor material. After creation of an electron-hole pair the two charges are separated due to an asymmetry which is created by doping the semiconductor material (or using two different semiconductor materials with opposite doping). The first solar cell was invented at Bell Labs in 1954 and used silicon wafers as semiconductor material. This material contributes today to ~90% of all PV products and is able, due to its abundance in the earth's crust, to easily supply semiconductor material for many TW of solar cells and modules, enough to become one of the five contributors for a future 100% renewably powered world.

The market for PV systems started in the 1950s/60s with powering of satellites and in the 1970s/80s with off-grid systems, consumer products and first pilot projects for large on-grid systems. In 1990 the first demonstration project for on-grid systems was started in Germany (1.000 roof program), followed by a 70.000 roof program in Japan. The key for success was the introduction of a feed-in tariff system in Germany (EEG, Renewable Sources Act) in 2000 which was adopted in similar form in more than 50 countries in the following years. With the principle of earning a decent return of invested money over a ~20 years period with guaranteed compensation for each produced kWh of electricity, this decade saw a never expected annual growth of ~ 50%, from 300 MW installed systems in 2000 to ~17.000 MW in 2010 (mainly in Europe) [16]. Since then more and more countries are eager to introduce PV as a growing important electricity contributor (China, Japan, US, India, South America and Africa).

This extraordinary growth was paralleled by a significant decrease in prices for all parts of a PV system, most pronounced for PV modules and inverters but also for BOS (Balance of Systems) and installation: the price for a PV module was ~6$/W in 2000 and dropped to less than 1$/W in 2010. Overall the LCOE for PV systems are today in the range of 10 to 20 $ct/kWh, depending on system size and region of installation. Cell efficiencies today are in the range 16 up to 23%, depending on wafer material and cell architecture.

Beside the wafer based crystalline Si-technology (today's market share ~90%) there is an interesting portfolio of additional technologies available: various thin-film technologies (amorphous Si, II/VI-compound cells (CdTe/CdS and CIGS) with the potential of roll to roll manufacturing on flexible substrates, dye solar cells with the potential to offer different bright colors determined by the specific dye, organic solar cells as well as III/V-compound cells.

The latter can not only be used to power satellites with high efficiency (43% in laboratory and ~40% in production with multi band-gap cell structures), but also for highly concentrating PV systems (~400 up to 1,000 times concentration). These concentrating PV (CPV) systems do need a high fraction of direct sunlight together with dual axis trackers and compete therefore with the concentrating solar thermal systems. Both technologies are well suited for large scale GW systems located in the sun-belt of our earth.

In the long run it is realistic to assume for the relative share a decrease for crystalline wafer-based products and an increase for thin-film technologies as well as III/V-compound solar cells. Precise numbers may be increasingly difficult to give as there might be developments which merge the existing technologies.

4.5. Other Renewables (including hydro, biomass etc.)

All other renewable technologies are also important but will individually contribute much less in relative terms:

- **Hydro:** based on a linear growth of 0.5 PWh every 10 years since 1965 and a cumulative production of 3.5 PWh in 2011 and even assuming the same growth for the coming 90 years there will be a limit of ~8 PWh/a
- **Bioenergy**: area efficiency too low for electricity production (factor up to 50) and fuel for transportation (factor up to 150) compared for example with PV
- **Geothermal**: only few local places with appropriate access to the needed high temperature environment are available to produce cost efficiently electricity
- **Wave and tidal**: the maritime environment creates many technical challenges for a cost effective and large scale electricity production and will most probably only allow for niche applications

5 SIMPLIFIED SPLIT FOR THE VARIOUS RENEWABLE ENERGIES FOR A 100% SECONDARY (= PRIMARY) ENERGY SUPPLY

The technical potential for the various Renewables has also been analyzed by WBGU [12]. The numbers for the technical potential can be seen in Table 5-1. In addition this group also worked on a so-called "sustainable potential" which takes into account important restrictions.

	Technical potential [PWh/year]	Sustainable potential [PWh/year]
Biomass	224	28.0
Geothermal	202	6.2
Hydro	45	3.4
Solar	78,400	2,800.0
Wind	476	280.0
total	79,347	3,117.6

Table 5-1: Global potentials for renewable energy sources
Source: WBGU Flagship Report [12]

The split between the major Renewable sources for the sustainable potential can be summarized as follows: 90% solar, 9% wind and 1% all other Renewables (including hydro). In order to minimize storage capacity and to integrate specific local renewable sources (hydro, geothermal, bioenergy, wave and tidal) we may decrease the contribution from solar down to 60%, increase the contribution from wind towards 20% and that of all other renewables also to 20%. The 60% solar may be divided into three roughly equal parts: decentralized PV, central power stations with CPV and CSP and solar heat (heating and cooling of houses, medium process heat for small industries). With most of the important renewable technologies providing electricity this universal secondary energy carrier will have a dominant share of about 2/3 (including the electricity for "Power to Gas").

6 IMPORTANT MEASURES FOR BALANCING VARIABLE RENEWABLE ENERGIES

The challenge for the future is how to optimize the supply of electricity with a best suited portfolio of various and variable renewable energy sources as needed. There are two issues to be optimized in parallel:

(1) Smoothening of the load curve at all levels (house, municipality and country) by Demand Side Management and other intelligent communication tools. The implementation of the "smart grid" within the low voltage region and the information exchange with future "smart homes" (including e-cars) will be important for success.

(2) Optimized portfolio with local renewables to meet on average the daily and seasonal power needs at lowest cost.

In most regions we have every year for a time period of up to two weeks a so called "Dark-dead Calm", meaning no sunshine and no wind in this time (in Europe often during the winter period). In order to minimize the use of combined heat and power stations and to further facilitate the smoothening of the load curve it is desirable to have cost efficient storage technologies available.

7 PRICE EXPERIENCE CURVE FOR Li - Ion BATTERIES

The strong predictive power of Price Experience Curves (PEC) has been described earlier for a number of mass products like semiconductor storage chips, flat panel displays and also solar modules (Hoffmann, Wieder and Pellkofer [6]). It was highlighted that even the experts in their own field most often could not imagine the quick price decrease for mass products.

A similar situation is today with the further development of electricity storage in batteries. Most experts look back and conclude that for electrochemical batteries – and they normally refer to the standard lead acid battery - no substantial price decrease is to be expected. But the introduction of electrodes with new high-tech materials could also substantially increase the number of cycles for this type of batteries from ~1,000 today towards 5,000 and potentially even more [17]. In parallel the cost for a stored kWh would significantly decrease: assuming a 5-fold increase of cycles and doubling of cost would roughly decrease the cost for a stored kWh by a factor of 2.5 (i.e. from today's 15-20 €ct/kWh down to 6-8 €ct/kWh) for such improved lead acid batteries.

This paper shows for the first time a PEC for a new type of batteries, namely the Li-Ion battery (LIB). It was first the mass introduction of cellular phones which needed this type of batteries in the Wh-capacity range [18]. Driven by the automotive industry for the introduction of electric vehicles (EV) there has been a substantial development for this type of batteries (which have a capacity in the kWh-range) accompanied by a rigorous price decrease. For both types of LIB's a PEC is shown in Fig. 1 and 2. The following conclusions can be drawn:

LIB for cellular phones (~Wh-range)
PEF ~>20% (up to 25%)
intersection between PEC and price level of 100$/kWh around 1 TWh of cumulative installed capacity

LIB for automotive EV's (~kWh-range)
PEF ~<20% (down to 15%)
intersection between PEC and price level of 100$/kWh around 1 TWh of cumulative installed capacity

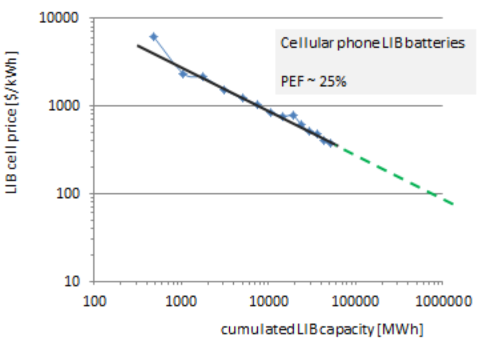

Figure 1: PEC for cellular phone LIB's, green dotted line is extrapolation of past PEC (raw data from personal communication C. Pillot (2014), avicenne)

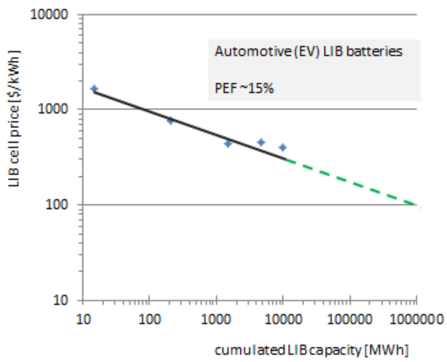

Figure 2: PEC for automotive (EV) LIB's, green dotted line is extrapolation of past PEC (raw data from personal communication C. Pillot (2014), avicenne)

Based on the experience with other PEC's it is highly probable that the future prices per kWh will occur around the mentioned cumulated volume. The unknown question is as to when it will happen – this depends on the growth rate in future years.

According to a recent report in Handelsblatt [19] market demand is higher than planned. BMW has sold in first half year of 2014 more than 5000 BMW i3 EV's and expect with the start of US sales the highest market demand in this country. Elon Musk with his start-up Tesla plans a 5 billion $ investment for a huge LIB factory. Many other car manufacturers have also EV's in their portfolio, including batteries for hybrid cars.

If we assume the year 2030 for the cumulative volume to be reached a CAGR for the cumulative volume of 31% is needed. Remembering that the PV industry demonstrated a CAGR of 41% between the years 2000 and 2010 the above CAGR for LIB's is ambitious but achievable from an industrial point of view.

In a recent study (personal communication C. Pillot (2014), avicenne) the development for kWh-LIB's both for the cell structure as well as the packaging cost was calculated based on actual numbers for 2012 and further development for 2015 and 2020. These cost numbers are shown in the upper part of Figure 3. An estimate for 2030/35 was made by the author by using the cell price from the extrapolation of the PEC and considering a further price decrease for packaging by a factor of 2, driven mainly by economy of scale. A simplified calculation for the storage cost can be made with the following assumptions:

1. Lifetime for LIB ~5,000 cycles
2. Financing cost over the lifetime ~ same as investment
3. Usable capacity per cycle 80%

With these numbers together with the respective investment (I) the cost per stored kWh can be estimated as

Cost per kWh stored electricity =
(I x 2) / (5,000 x 0.8)

The result is seen in the lower part of Fig. 3 and starts with ~20 €ct/kWh in 2012 towards ~15 and 10 €ct/kWh in the years 2015 and 2020, respectively. With LIB cost of 125 $/kWh the storage cost decreases towards 5 €ct/kWh, which would be a great achievement both for EV's and stationary storage. Using an electricity consumption of 20 kWh/100km for EV's the price per 100 km would then only be (2-3)€ (1€ for storage plus (1-2)€ for electricity from wind and solar), compared with (6-12)€ for a petrol driven car ((4-6)l/100 km x (2-1.5) €/l). Also for self-consumption the compelling figure for a PV-kWh on demand (i.e. stored in a battery) would only be (5-10)€ct/kWh PV plus 5 €ct/kWh storage giving (10-15)€ct/kWh, which may be compared with today's residential prices of electricity with ~(20-30)€ct/kWh; these decentralized prizes are even comparable with electricity generation prices from new nuclear plants or new clean fossil (with Carbon Sequestration and Storage) plants without any transmission cost and taxes.

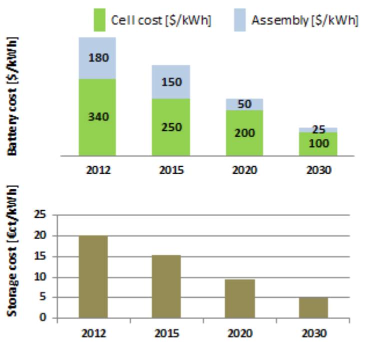

Figure 3: (upper part) LIB cost development for automotive (EV) batteries, both for cell and packaging cost; (lower part): development for estimated storage cost per kWh. Data for the years 2012, 2015 and 2020 from personal communication C. Pillot (2014, avicenne), data for 2030 are extrapolated from author.

For commercial applications and larger storage capacities there are already suitable battery technologies available, like NaS and redox-flow. SME's and municipalities could effectively use these batteries to store surplus of renewable electricity by wind and solar PV within the respective low-voltage smart grid.

For even higher capacities municipalities have already started to pilot the so called "Power to Gas (P2G)"- technology. Surplus of electricity from wind and PV farms are used to produce first hydrogen by electrolysis from water which is then transferred to methane by reacting with CO_2. This methane can then be fed into the existing gas infrastructure to be used at a later point in time either to produce heat by burning, with CH&P-systems to produce heat and electricity or with fuel cells for electricity.

8 SUMMARY AND OUTLOOK

Based on an increase of energy efficiency by an ambitious but realistic factor of 3 it is shown that a future world with ~10 billion people could be powered with ~150 PWh secondary energy (90 PWh today) within the second half of this century. This would even have no longer the inequity of today where only ¼ of today's population uses ¾ of the primary energy, but on average everyone would have a similar energy consumption and poverty could effectively become history.

The sustainable offering from all renewables of ~3,100 PWh/year has a breakdown of 90% solar, 9% wind and 1% all other (including hydro-power). Considering advantages of local renewables like hydro, geothermal and some others together with minimizing storage and using the complementary delivery between wind and solar during the seasons it is estimated that PV will have a contribution of ~20%, large power stations of CPV (Concentrated PV) and CSP (Concentrated Solar (thermal) Power) ~20%, solar thermal ~20%, wind ~20% and all other the remaining 20%. Given the fact that the most important renewables produce electricity, this secondary energy form will provide ~2/3 of the total. Emphasis is given that the 20% PV which equals 30 PWh electricity, could well be installed as early as in 2050 with realistic growth rates until then. Efficient isolation including ventilation will drastically reduce the need for heating and cooling; transportation is assumed with electricity (either directly, with hydrogen and fuel cells or methane (Power to Gas or P2G) and gas motors).

Market growth stimulated by support schemes like the Feed-in tariff has propelled the market volume in a rather short period of time with accompanying continued decreasing prices. Based on the fact that we have already achieved today parity of levelized cost between electricity produced either traditionally with fossil (including CSS = Carbon Sequestration and Storage) and nuclear or PV and wind, the cost advantage for renewables will even increase in coming years. This is supported by continuing the Price Experience Curves for the respective renewable technologies and integrating this into a complete system cost analysis. An estimate of material cost and obtainable efficiencies shows that there is considerable room left to further drive down the module but also the total system price with increased cumulative volume.

As we move towards a 100% renewably powered world it becomes increasingly important to include cost efficient electricity storage. A first estimate for a Price Experience Curve for Li-based batteries has been shown together with some implications. New materials for traditional batteries will also contribute to a substantial price decrease for battery storage.

As we move from a level today between 5 and 10% PV produced electricity of a countries annual electricity consumption (like Germany, Italy and Greece) towards 20% and more we need to balance the supply of the variable PV (and all other electricity generating sources) and the load from consumers. There will be a variety of electricity storage products to accomplish this: small batteries in households, medium to large batteries at the municipality level and very large using pumped hydro as well as usage of the existing gas network with "Power to Gas" (P2G produced by surplus wind and solar electricity). Remaining power needs could be served with many decentralized CH&P systems which could be provided in many cases with future range extenders in electric vehicles. The latter could be done in the most environmentally friendliest way if the range extender was a fuel cell driven by hydrogen or P2G. Local autonomy within the future low voltage smart grid area for private homes, SME's, hotels and offices will be seconded by either locating the energy intensive industry to the central renewable power plants (hydro, off-shore wind, CSP and CPV) or connect them with HVDC transmission lines.

With annual market growth numbers well proven by the industry to be realistically followed, the world could reach as early as 2050 a 100% energy supply only by renewables. There is clear evidence that there are no limits with respect to critical materials needed, neither in terms of availability nor with respect to environmental concerns. Whether the ambitious goal of 100% renewable technologies is reached by 2050 on a global level may be judged differently, especially by knowing that the last 10% are the most difficult. After all it will be the superior economics which ultimately drives the world away from current fossil and nuclear technologies towards renewables. It will be the financial world which will lead this development when realizing that the portfolio of decentralized renewable technologies has a significant cost advantage over traditional centralized fossil and nuclear technologies.

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