

# Combining Wind And Solar With Energy Storage To Achieve The Greatest Economic Value

Presentation of Dr.-Ing. Matthias Popp  
at

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Energy Storage Forum Europe 2012 Rome



Ladies and Gentlemen,

let me introduce myself and give you some information about my office.

## Dr.-Ing. Matthias Popp

- born 1958
- Wunsiedel in Fichtelgebirge, Bavaria
- 1983 founding of Engineering Office Popp during study
- 1983 diploma in mechanical engineering at Fachhochschule Coburg
- Engineering Office Popp, software development for automotive industry
- 1989 diploma in mechanical engineering at Technical University Munich
- Member of city council (CSU) and from 2002 to 2008 honorary deputy mayor of his home- and festival town Wunsiedel in Fichtelgebirge as well as member of the supervisory board of the regional energy provider SWW Wunsiedel GmbH

Thereby intensive involvement with questions of energy supply

The proposal for a pumped hydro power station in the Fichtelgebirge was leading to the research for answers to the question:

**How can energy storage plants deliver a contribution to a sustainable regenerative power supply?**

- 2010 doctor-engineer at Technical University of Braunschweig
- 2011 finalist at the RWE Future Award 2011

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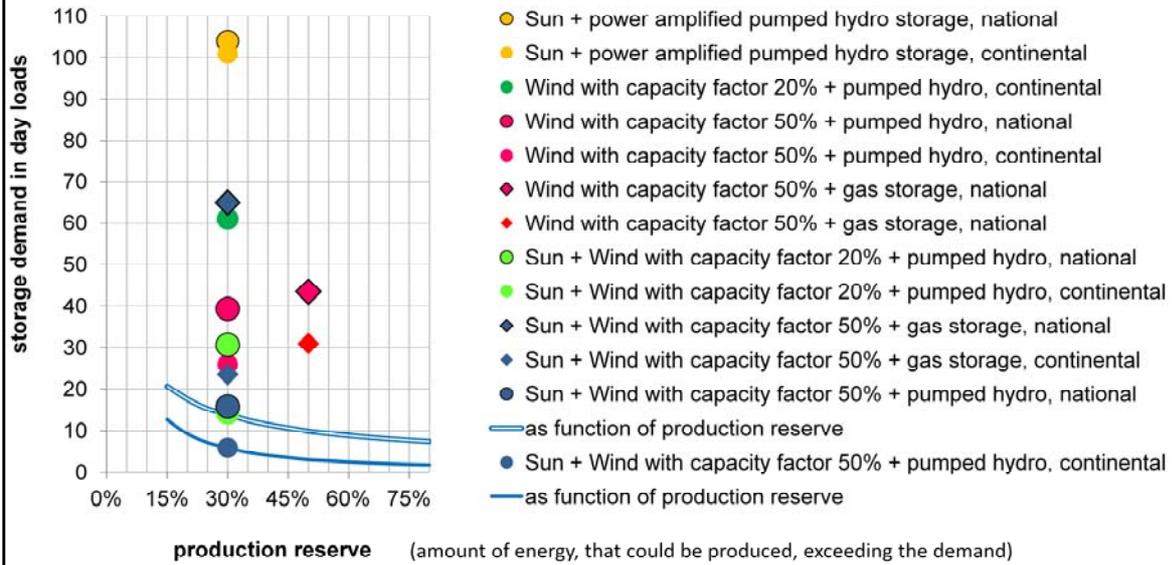


In 2010, I made a doctorate with the title:

„Storage demand for a power supply with renewable energies“.

This doctoral thesis is published as book by Springer in German language.

## Storage Demand for Germany with different adaption of wind and sun



Assumptions: pumped hydro storage efficiency 80%; gas storage efficiency 40%, no self discharging; long distance power transmission efficiency 95%

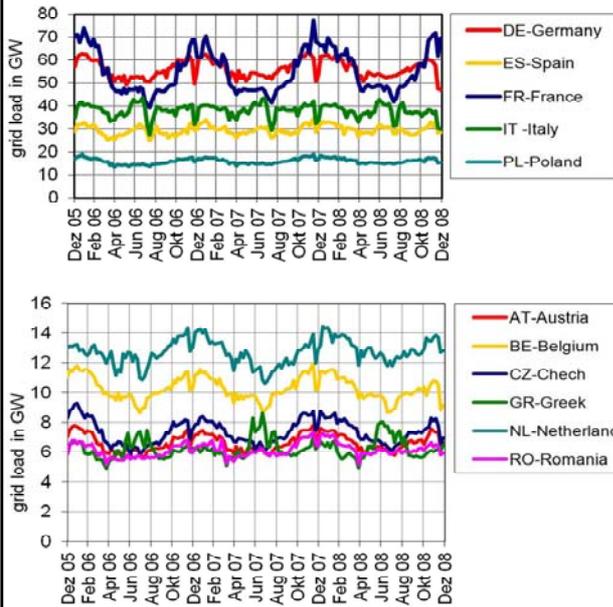
Every entry in this figure shows a solution for a regenerative electric power supply system, based on wind and sun, that meets the demand.

A day load is the, in average, daily consumed, amount of energy in the supplied area.

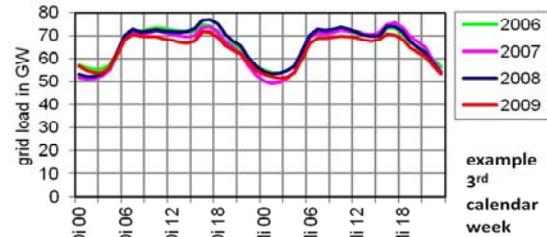
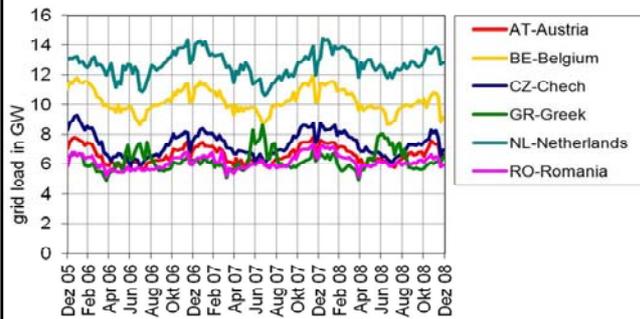
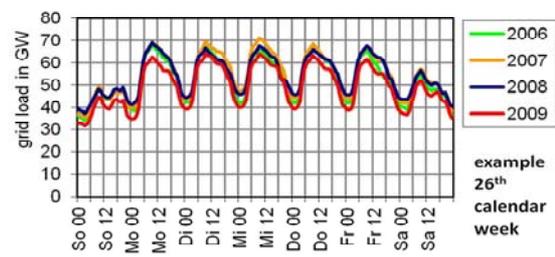
The better the tuning between wind and sun, the cooperation between countries, based on well developed transmission grids and the higher the chosen production reserve and the higher the storage efficiency, the lower the required storage capacity will be and vice versa.

# Consumption of electric Power

weekly power consumption in European countries



daily power consumption in Germany



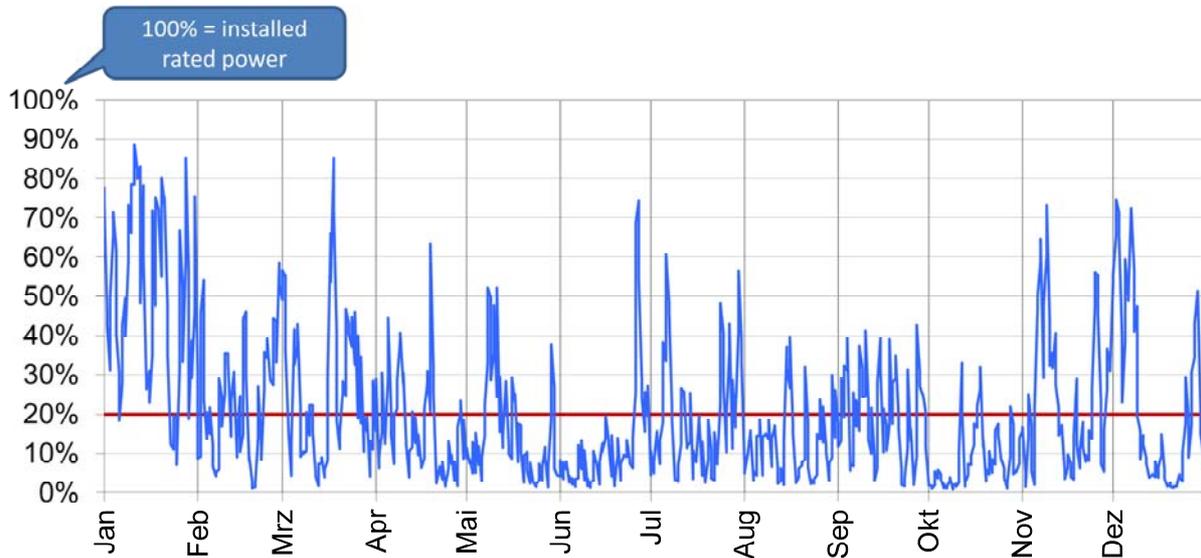
In European countries, the consumption of electric power during winter time is normally higher than during summer time.

It shows a typical sequence over the days of a week, according to the time of the year.

A power supply has to fulfil this task precisely in every moment, independently from the power production system.

## Characteristics of Wind Energy

real wind power input in Germany exemplary for 2005 (blue)  
capacity factor about 20% (1750 full load hours)



The maximum installed generating power of the wind power plants in Germany is never produced, because there is hardly a constant strong wind across the whole country.

Sometimes, there are countrywide weak wind phases, where the wind power production goes almost down to zero.

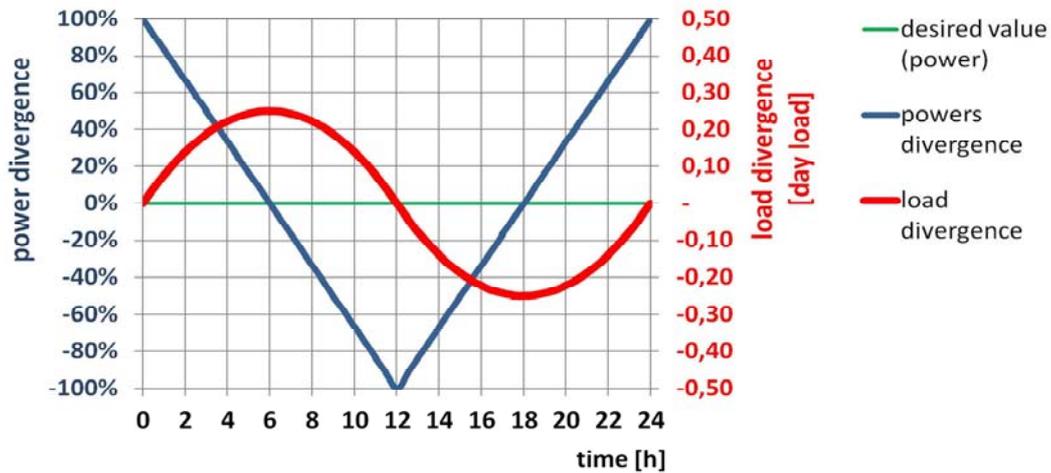
When wind power production isn't enough, to fulfil the intended power supply task, other external power stations have to help out to balance the deficit.

In average, wind power plants in Germany deliver about 20% of their installed power.

To determine the necessary storage properties for balancing between surpluses and deficits, the load divergence is introduced.

## Load Divergence

as characteristic feature of volatile power sources



It shows, how an ideal storage system without losses has to be operated, to transfer a volatile power production into a constant power supply.

Overshooting power charges the storage system and power deficits discharge it.

At the end of the analysed period, the storage system has the same zero load level as at the beginning.

Mathematical, it is the power divergence from the average power, integrated over the time.

## Wind Energy in Europe – Data Basis



Raster areas  
90 km x 90 km

Wind speed  
100 meters above  
ground

1970 to 2008

3-hourly time steps

Source:  
anemos Gesellschaft für  
Umweltmeteorologie mbH

With the concept of load divergence, the wind energy of Europe was analysed.

In three hourly time steps, available wind power for all European countries was calculated by using characteristics, orientated on real wind power stations.

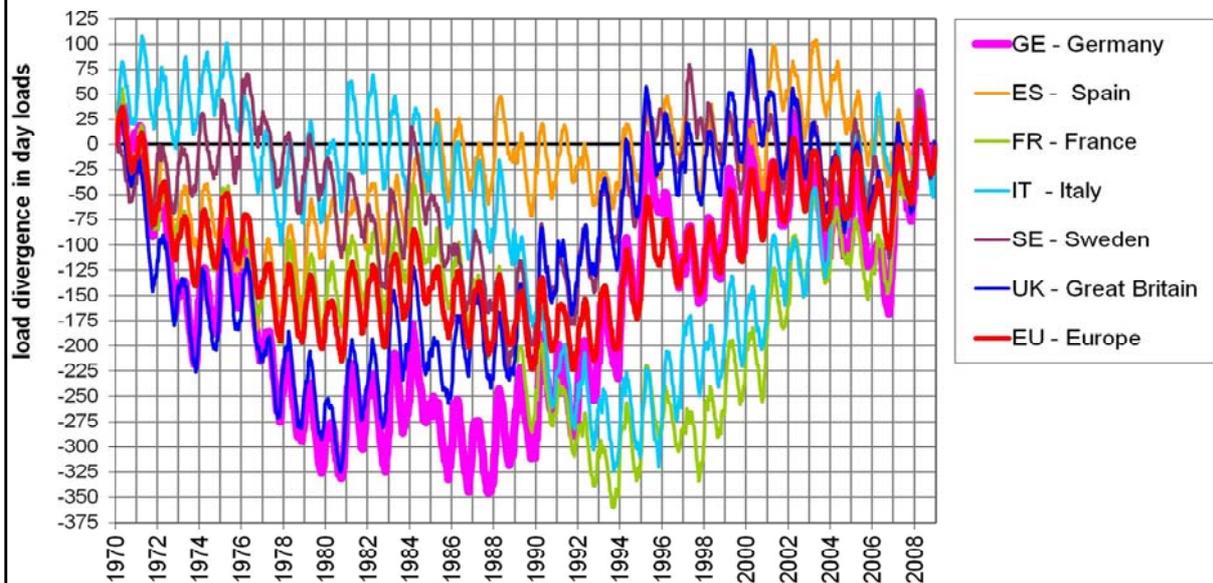
The comparison of these calculated values, with the real wind power inputs in Germany, showed good conformance.

This validation created confidence in the used procedure.

Let's now have a look at the identified load divergences.

## Load Divergence of Wind Energy in Europe

for wind power plants with capacity factor 20%



Shown are the load divergences for some large European electricity consuming countries and for whole Europe.

In weak wind periods, storage devices would have been discharged, in strong wind periods, they would have been charged.

At the end of the analysed period, where the same amount of electrical energy would have been produced as consumed, the load divergence is zero, like at the beginning.

The curves show drastic differences in the yearly availability of wind energy in different countries.

The load divergences increase and decrease during this period in some countries to values as large as the power consumption of a whole year.

Because of average stronger winds during winter time, an increase of load divergence can be observed.

Because of average slower wind speeds during summer time, a decrease of load divergence can be observed.

The load divergence, caused by the wind power, depends strongly on the design of the wind power plants.

## Increasing the Capacity Factor (number of full load hours)

- larger rotor diameters
- larger hub height in air layers with higher wind speeds

wind power

- increases with the square of the rotor diameter  
**double diameter => fourfold power**
- increases with the third power of the wind speed  
**double wind speed => eightfold power**

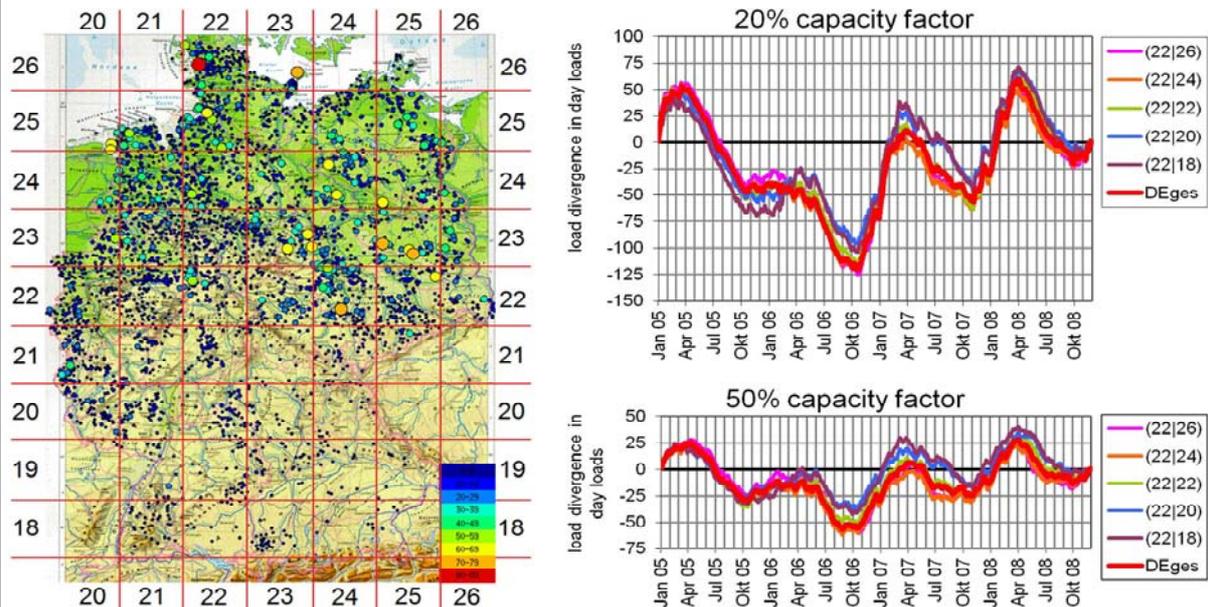
When keeping the rated power of a wind power station and increasing the rotor diameter as well as the hub height, the average power and therefore the capacity factor will increase **at a clearly reduced load divergence.**



If wind energy plants are designed for a larger number of full load hours, or meaning the same, for a higher capacity factor, the load divergence of the transformed wind energy can be reduced drastically.

Some manufacturers offer wind power stations, leading into this direction.

## Capacity Factor and Load Divergence



Broken down to the conditions of Germany, the map shows the raster areas of the used European wind atlas.

Comparing the load divergences of the single areas of Germany, it can be seen, that the curve shapes are very similar.

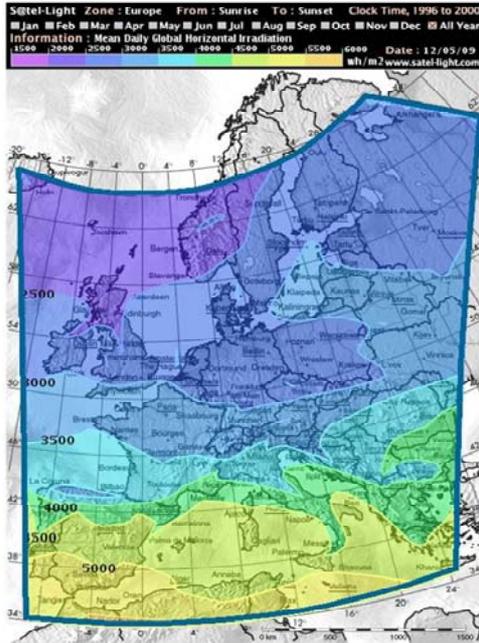
The diagrams show exemplary for four years, from north to south, the load divergences of some areas.

The similarity of the curve shapes comes from the observation, that wind conditions normally follow the weather conditions of greater areas, surpassing far over the borders of single countries.

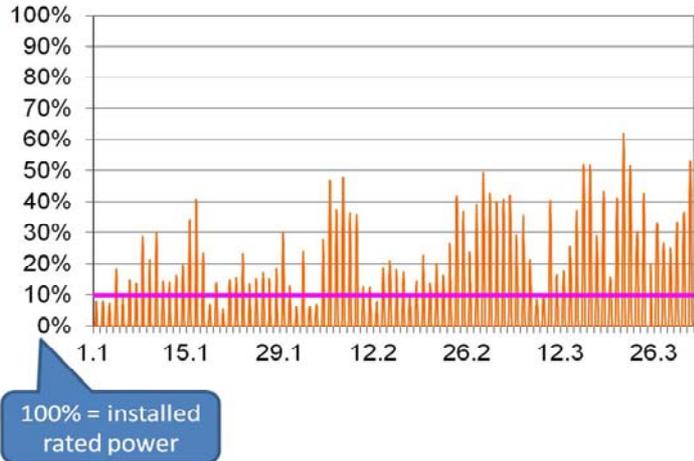
The balancing effect of a powerful electricity grid in a national solo run will therefore stay within borders.

However, a higher capacity factor would have a much bigger balancing effect.

# Solar Energy Offer



real solar power input in Germany  
 in the 1<sup>st</sup> quarter of 2005 (orange)  
 capacity factor, applying to the whole year about 10%

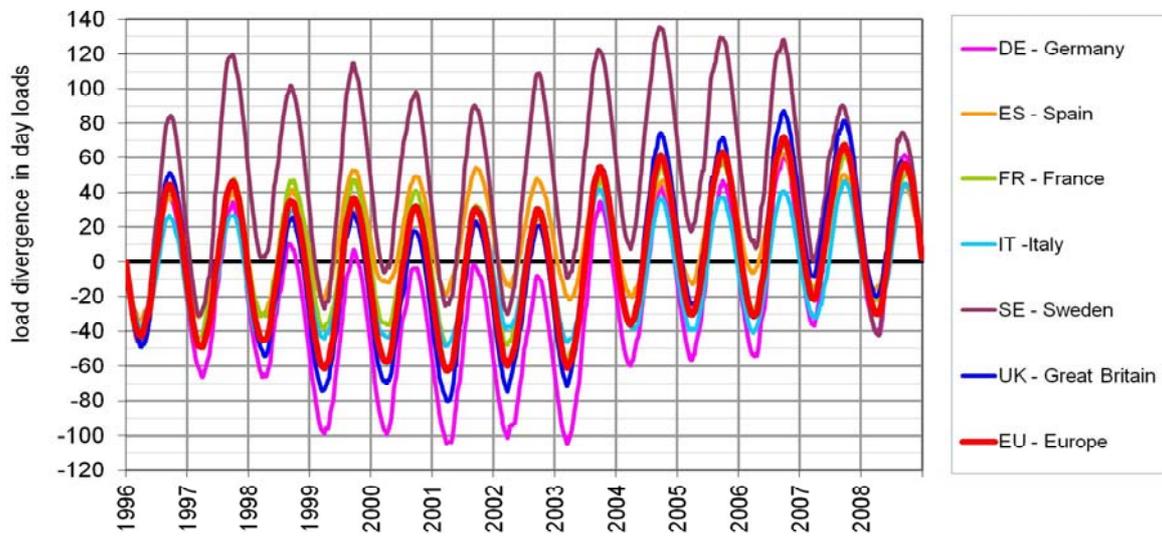


For these studies, global irradiation measurements from meteosat satellite where available.

The known curves of sun power, as daily pulses, reach in Germany in long term average about 10% of the installed peak power of solar modules.

Also for the solar energy input, the load divergences were calculated.

## Solar Energy Load Divergence

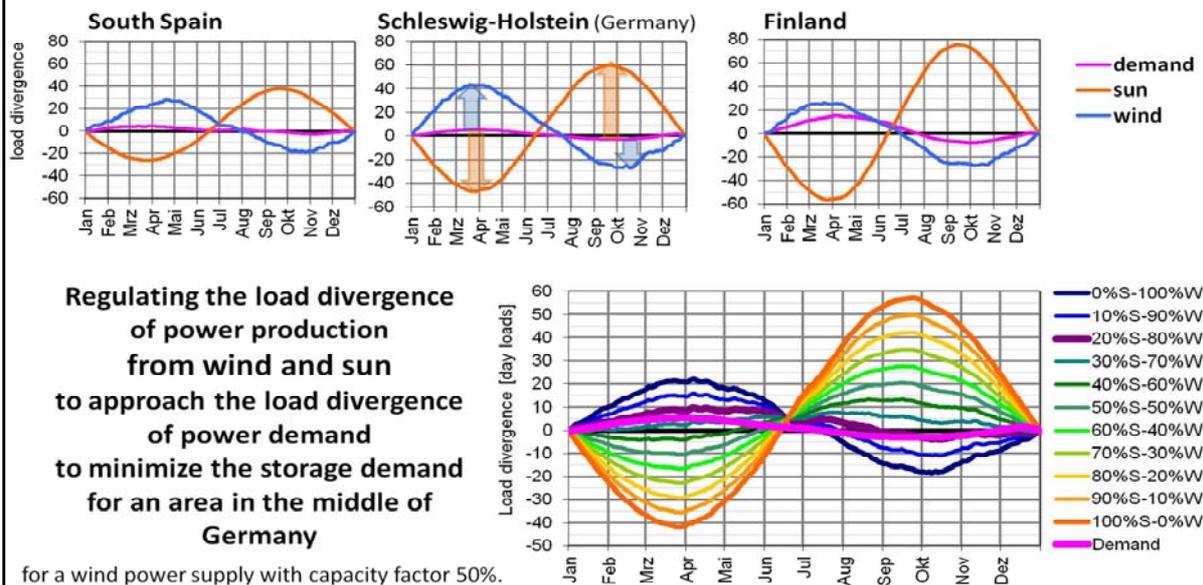


As awaited, the diagram shows, that storage systems would fill up during summer time and would empty during winter time.

Thereby, the load divergence of solar energy behaves about in opposite manner to the load divergence of wind energy.

## Yearly Average of Load Divergence

for the power demand as well as for the solar and wind power availability in example regions



for a wind power supply with capacity factor 50%.

To illustrate those circumstances, the analysed period is merged together to one year for the three load divergences of power demand, wind power and solar power.

The sum of the blue arrows in the example for Schleswig-Holstein gives the storage capacity, necessary to balance the wind energy for a power supply, meeting the demand, in this region.

The sum of the orange arrows shows analogical the storage demand for balancing a pure photovoltaic power supply.

The production contribution of wind and sun can be tuned for every region and for every country so, that in sum a minimum of divergence from the regional demand would result.

With this discovery of an optimal mixture of energy production, the necessary storage capacity can be minimized.

## Secure Real Power Supply with Production Reserves

### Production reserves

serve beside the

**balancing of storage- and transmission losses**

also the

**ability to bridge over years with higher power demand and/or lower production with limited storage.**

Real power supply systems must get along with lossy storage systems and with lossy power transmission grids.

Storage systems can furthermore only dispose over a limited capacity and transmission grids can only dispose over a limited transmission power.

In order to establish a secure and always meeting the demand power supply, production reserves are required.

They allow, in average, to transform more volatile power to electrical power, as really requested.

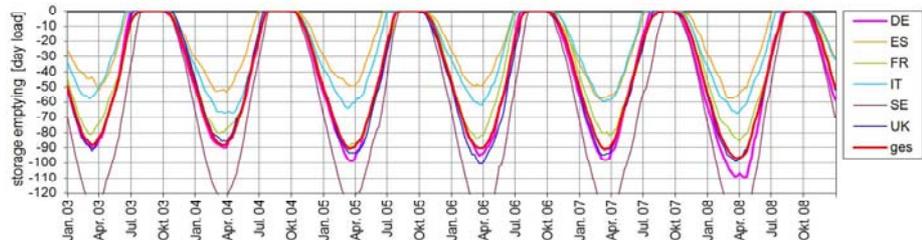
Production reserves are necessary, to fill up storage systems again, after low production periods.

The storage management, that would arise under real, technical realisable conditions is shown in the following storage emptying curves.

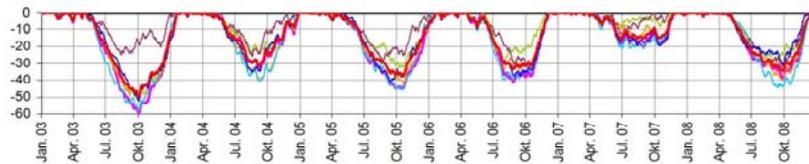
## Storage Emptying Curves with 30% production reserves

solar energy  
with pump power amplified  
storage devices

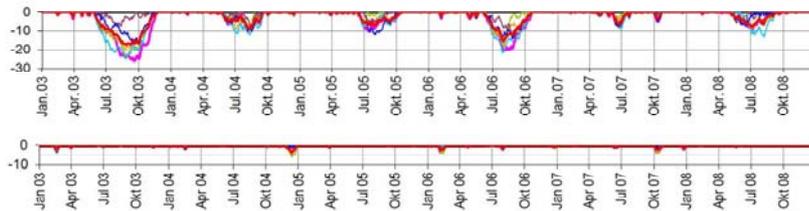
with 80% storage efficiency  
and powerful continental  
networking



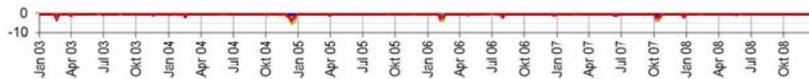
wind energy with  
capacity factor 20%



wind energy with  
capacity factor 50%



optimized combination  
of sun and wind  
with capacity factor 50%



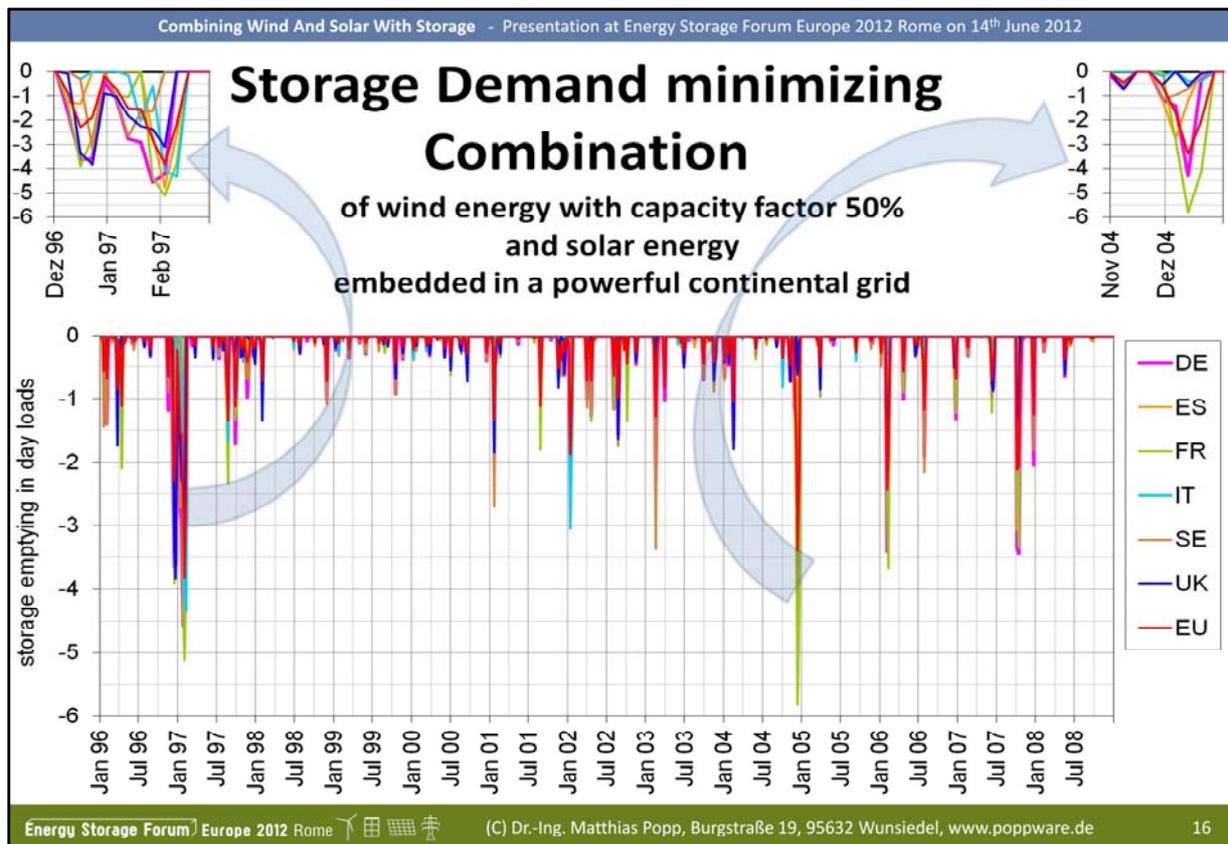
Assuming a given pure photovoltaic production system, the maximum discharge of a storage system would account more than 100 day loads at the end of the winter.

A pure wind energy production, which has in the moment a capacity factor of about 20% in Germany, would lead to a maximum storage discharge of 60 day loads at the end of the summer.

Using wind energy with a higher capacity factor, the storage demand could be reduced to about 26 day loads.

An optimized mix of both types of energy production would drastically reduce the maximal necessary storage capacity.

Those circumstances are shown in the next diagram in a larger scale and for a longer period of time.

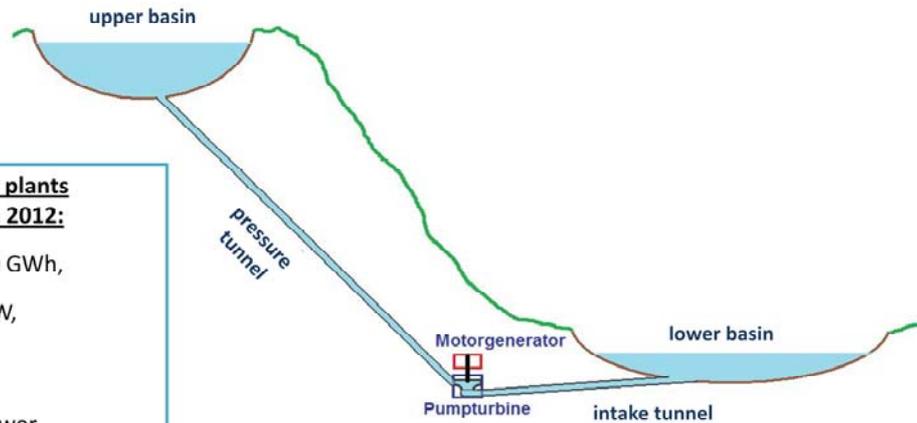


It can be seen, that only after a couple of years, during winter time, a significant use of the storage capacity would occur.

Often, storage systems would be stressed less than a half day load over many months.

Mostly, the storage systems would be well charged.

## Pumped Hydro Storage



### storage power plants in Germany in 2012:

- capacity about 40 GWh,
- power about 7 GW,
- equates to about **1/36 day loads** of the average power consumption in Germany,
- With it can be bridged about 10% of the countries power demand for about six hours

**For the storage of one kilowatt hour, one tonne of water has to be lifted to a height of 400 meters.**

That corresponds to about the hourly irradiated solar energy per square meter of the earth disc.

The available pumped hydro storage capacity of Germany correlates to about the 36-th part of a day load.

For a regenerative power supply of Germany, based on wind and sun and without fallback to fossil or nuclear energy carriers, that would mean, ...

## Required Storage Capacity

### **Storage demand in an isolated national initiative of Germany:**

in an optimized production structure with electric power, alone from wind and sun, with 30% production reserve

capacity about 20 TWh, power about 90 GW

corresponds to about **14 day loads** of the average consumption,

requires about **500 times the existing pumped hydro storage capacity**

### **Storage demand of Germany in an European cooperation:**

in an optimized production structure with electric power, alone from wind and sun, with 30% production reserve

capacity about 9 TWh, power about 90 GW

corresponds to about **6 day loads** of the average consumption,

requires about **200 times the existing pumped hydro storage capacity,**

**efficient upgrading of the European power grid and a complete upgrade of wind- and solar energy in all countries of Europe**

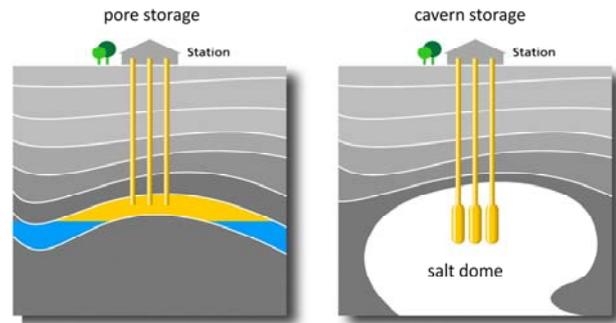
... , that in a national solo run, the actually available storage capacity would be required about 500 times as large.

In an optimized European cooperation, which unfortunately can't be expected today, the required storage capacity would still reach about 200 times of the existing capacity.

# Gas Reservoir

## Gas Reservoirs in Germany:

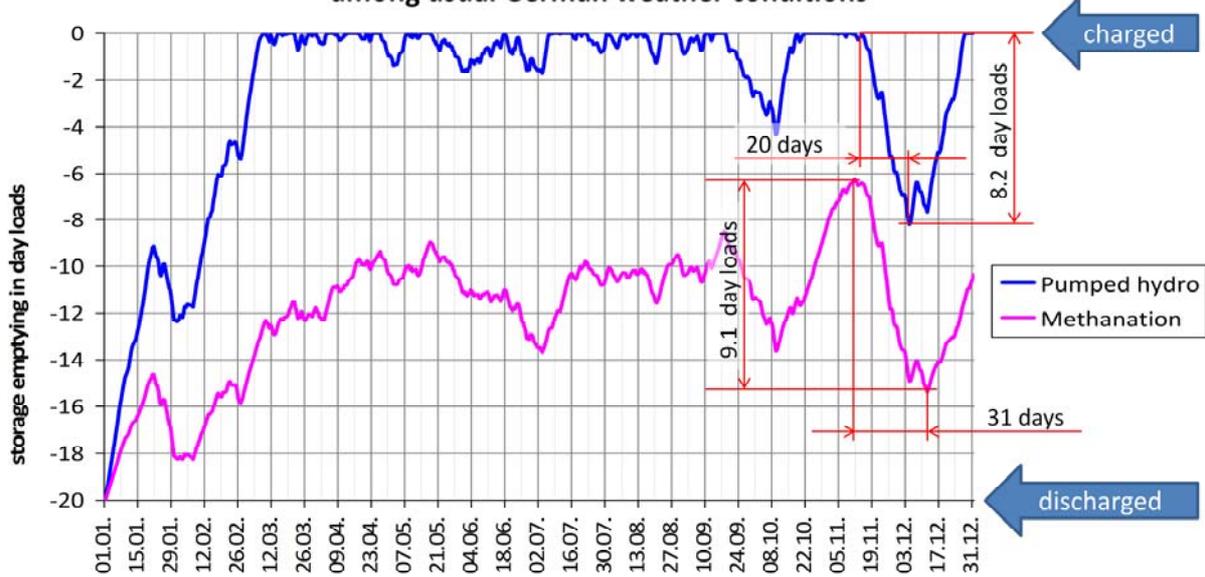
- Total storage volume about 35.000 Mio. m<sup>3</sup> V<sub>n</sub>
- Maximum working gas volume about 20.800 Mio. m<sup>3</sup> V<sub>n</sub>
- Energy content of natural gas about 10 kWh/ m<sup>3</sup> V<sub>n</sub> = 10 GWh/Mio. m<sup>3</sup> V<sub>n</sub>,
- Energy storage capacity about 208 TWh
- Efficiency of electricity generation (combined-cycle plant, GuD) about 60%
- **Electricity storage capacity** about **125 TWh**, that corresponds to about **87 day loads** of the average electric power demand of Germany



Because of the huge storage demand, caused by the future development of renewable power supply, alternative storage technologies are considered, with hydrogen or methane as energy carriers.

In contrast to the approved pumped hydro technology, the required storage capacity seems to be no problem, but much larger power losses would arise.

### Storage System Usage with high and low efficient systems among usual German weather conditions



76% vs 38% storage efficiency | wind could deliver with 100% as much energy as consumed, demand oriented allocation of the equipment across the country, capacity factor 50%, combined with 20% solar and 10% renewable base power e.g. from rivers, biomass, geothermic | electricity grid with the ability to remote transmit 50% of the countrywide demand.

Longer weak wind phases will define the future challenge for storage systems and no longer the balancing between day and night.

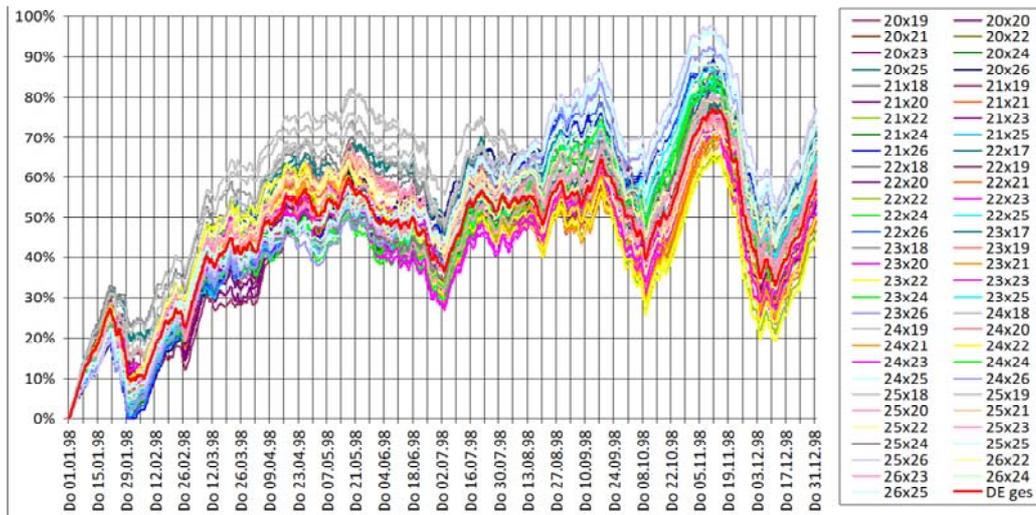
During long lasting and country wide affecting meteorological conditions, neither a powerful electricity grid, nor a smart grid solution can fulfil the task.

If not a powerful conventional, on demand available production park shall be established and kept in standby state, storage systems, designed with the necessary capacity reserves, will be required to meet this challenge.

As soon as these systems will be available, neither network expansion, nor smart grid solutions, nor short time storage systems are needed.

Short time storage and demand site management can than be fulfilled by the long time storage systems.

## Storage Charge Development with Gas as Energy Carrier



Demand oriented allocation of 100% wind, 20% solar and 10% base load, storage with 38% efficiency, 50% capacity factor of wind energy, **transmission power oriented to the maximum export capability**

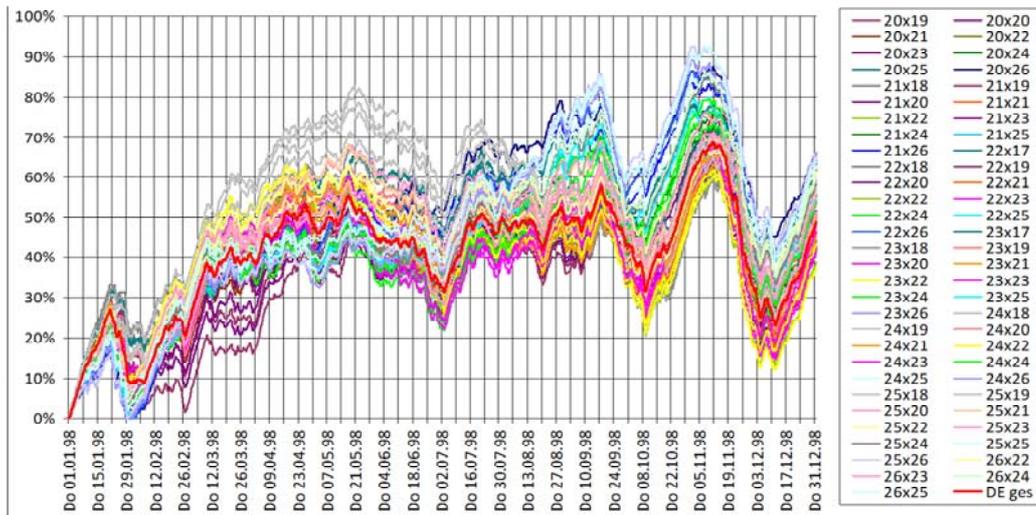
This results follows from the analysis of an optimized renewable electricity production system with an ideal allocation over the German country, based on raster areas with 90 times 90 kilometres as shown before on slide 10.

This chart shows charging and discharging of the assumed storage systems in every region of Germany for one exemplary year.

It belongs to storage systems, based on methane as energy carrier, in combination with a maximum power transmission grid.

An important result of this analysis, with real weather data, is, that the volatility of power availability in all regions of Germany is quite similar.

## Storage Charge Development with Gas as Energy Carrier

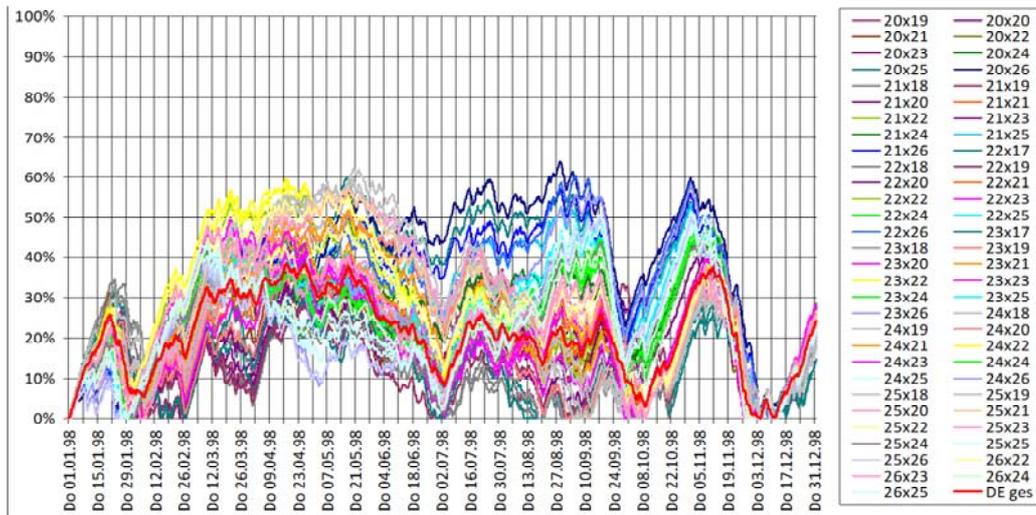


Demand oriented allocation of 100% wind, 20% solar and 10% base load, storage with 38% efficiency, 50% capacity factor of wind energy, **transmission power limited to 50%** of the export capability

If the same production structure would be operated with a transmission grid, that could maximal transmit 50% of the regional power demand, the storage charge would rarely change.

At the end of the exemplary shown year, the storage load is about 10% lower.

## Storage Charge Development with Gas as Energy Carrier

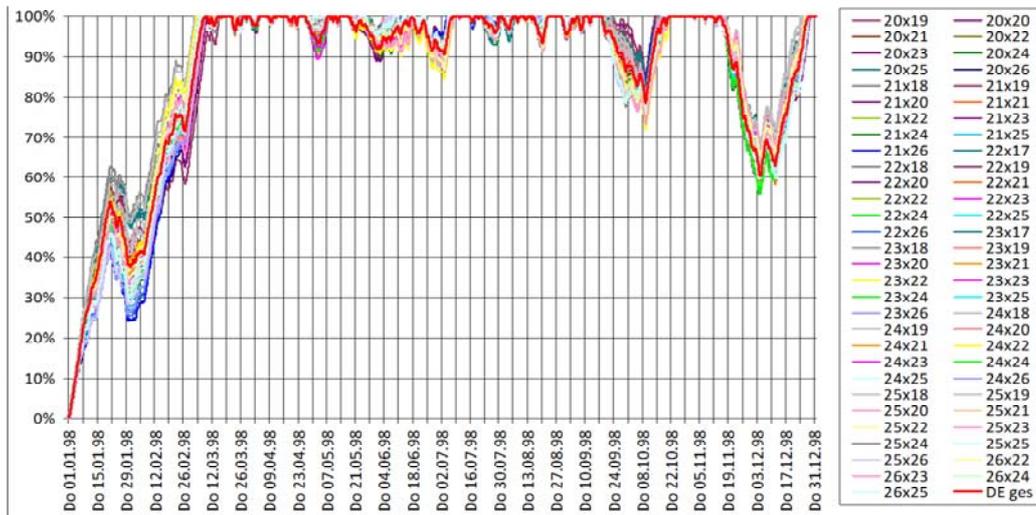


Demand oriented allocation of 100% wind, 20% solar and 10% base load, storage with 38% efficiency, 50% capacity factor of wind energy, **no transmission power (regional autarky)**

Even if theoretical, no long distance transmission power at all would be available, the storage systems would nearly have been able, to provide a secure power supply all over the year.

With a slightly larger production reserve, even this design of energy system would lead to a functioning power supply.

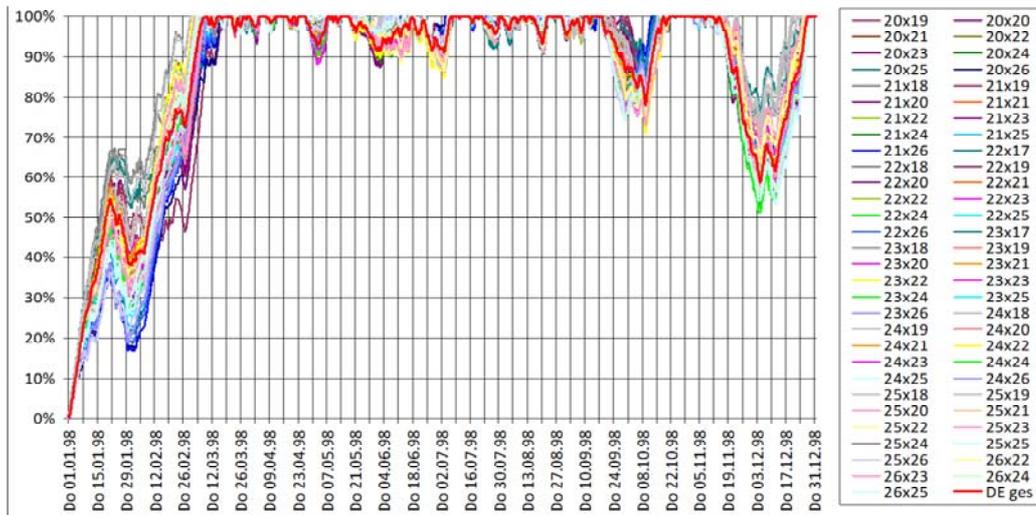
## Storage Charge Development with Pumped Hydro



Demand oriented allocation of 100% wind, 20% solar and 10% base load, storage with 76% efficiency, 50% capacity factor of wind energy, **transmission power limited to the maximum export capability**

If the same production structure as before would not be balanced with low efficient gas storage systems, but with high efficient pumped hydro storage systems, the storage devices would charge much faster because of clearly lower efficiency losses.

## Storage Charge Development with Pumped Hydro

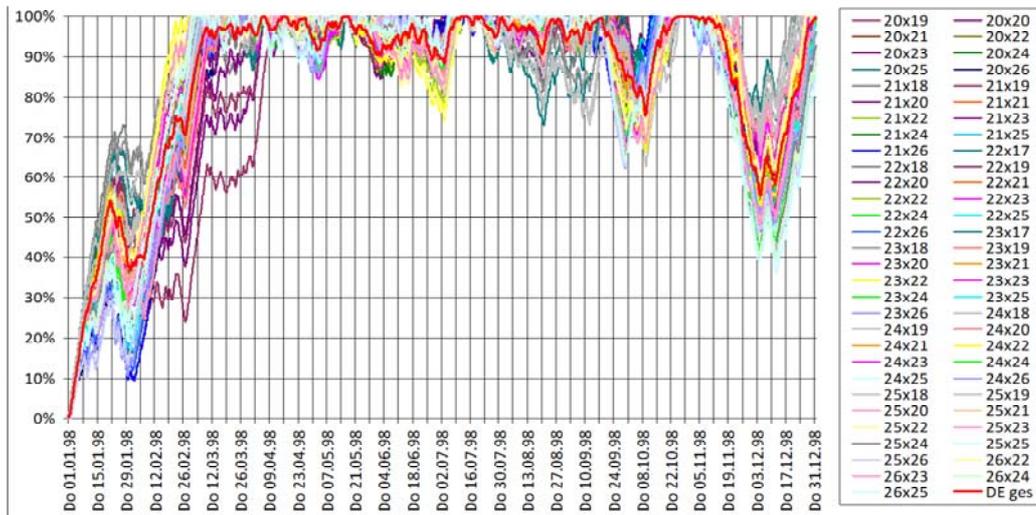


Demand oriented allocation of 100% wind, 20% solar and 10% base load, storage with 76% efficiency, 50% capacity factor of wind energy, **transmission power limited to 50%** of the export capability

A power grid, that could transmit only 50% of the regional demand, would hardly change the quality of supply.

Storage demand, to bridge the longest calm wind phases would increase only marginally.

## Storage Charge Development with Pumped Hydro

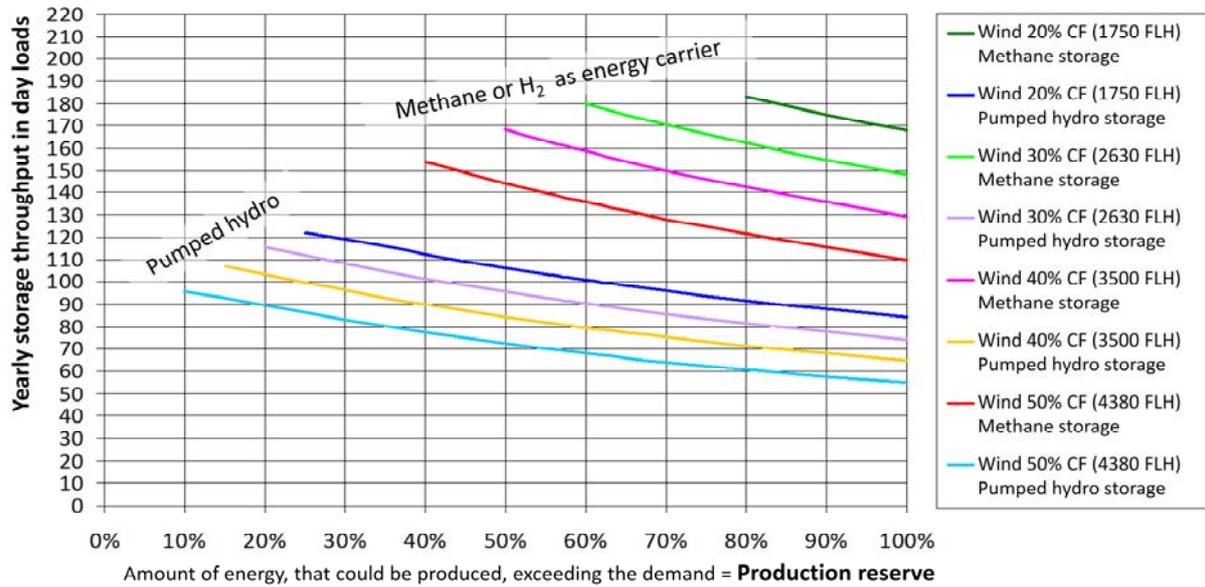


Demand oriented allocation of 100% wind, 20% solar and 10% base load, storage with 38% efficiency, 50% capacity factor of wind energy, **no transmission power (regional autarky)**

Even if no long distance transmission power at all would be available, the storage demand to bridge calm wind phases would overtop the storage demand with best transmission conditions with only about 20%.

A secure power supply without a supra-regional power grid could be realized.

## System Design and Storage Throughput



Yearly storage throughput at an autarkic power supply in a north Bavarian region. Assumption is an optimized regional adjustment of the use of wind and solar energy in dependence of the system design as shown in the legend, with additional 10% regenerative basic power.

A reason for the good applicability of pumped hydro systems, is the storage throughput.

That is the total amount of the yearly energy to charge the storage devices.

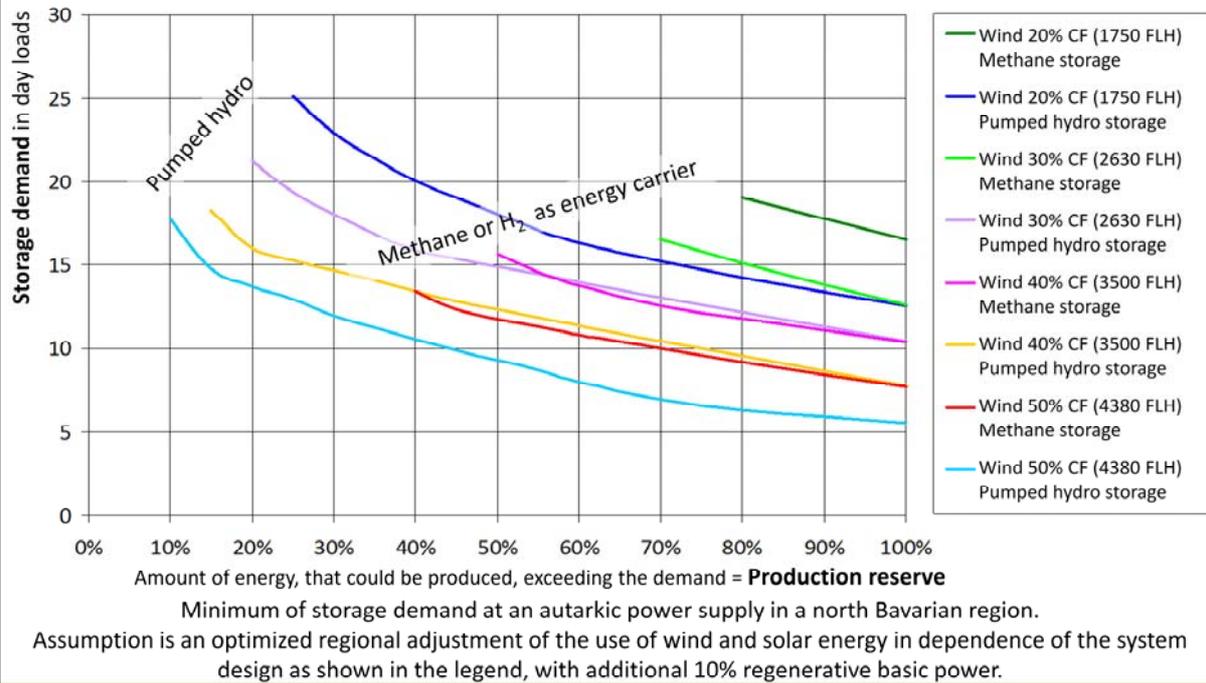
The amount of dischargeable energy is reduced with the energy losses.

Large energy losses, taking place during a storage process, don't accrue with high efficient storage systems.

They require less storage throughput and less production reserve, to achieve a stable power supply.

It will be an economical question, which storage solution, in an holistic approach, will open the more attractive development corridors.

## System Design and Storage Demand



The design of the production system, as well as the storage efficiency, has significant influence on the necessary storage capacity.

The required capacity is determined from the singular maximum of expected storage discharge in a long time consideration.

The characteristic lines show the minimum of necessary production power and the largest amount of expected storage discharge.

The obvious advantage of high efficient storage systems is, that less wind and solar power systems are needed, to achieve a secure power supply.

The higher the production reserve and the better the tuning of the production systems to the regional requirements, the lower the storage capacity will be.

If the combination of wind and sun isn't designed to minimize storage demand, the required storage capacity, the required production reserve and the macroeconomic costs of the renewable energy system would become clearly larger.

## Conclusion

A secure, robust and meeting the demand,  
100% regenerative power supply requires today:

- one wind power station for about 1300 people,
  - about 20 m<sup>2</sup> solar module area per person,
  - about 40 m<sup>2</sup> water area per person
- for power storage plants with high efficiency,  
decentralized, distributed well over the country.

That requires in Germany about 1% of the countries area.

Compared to this, a 100% electrical power supply with biomass would require about  
2200 m<sup>2</sup> per person or nearly half of the countries area.

Today, a secure and 100% regenerative power supply, which meets the demand, is a real option for the future.

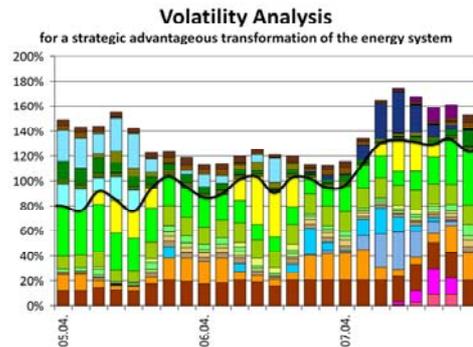
There are a lot of different possibilities, to realize it.  
But for every region, a suitable combination of wind and solar with energy storage can be determined, to achieve the greatest economic value.

Volatility analysis is called the calculation method, to find out optimized corridors for macroeconomic favourable renewable energy systems in a holistic approach.

It is less of a technical or financial challenge, than much more the question of winning understanding and acceptance in the society.

## Thank you for your Interest

**With a well-considered, holistic strategy, stakeholders in the energy market can bring themselves in an opportune position, when in future, regenerative power shall not only complement, but replace conventional power.**



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In the near future, important changes in energy economics will take place.

I hope, my presentation will motivate you and contribute to a holistic strategy, for a economic advantageous transformation of the energy system.