Future Energy Systems – Autonomous Control, Self-sufficient Energy Infrastructures and Big Data

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Abstract. The paper describes in a holistic manner the structure of the future energy system according to the targets and the framework of the German "Energiewende". This system is based on volatile and dispersed renewable energy sources. With respect to the existing infrastructure a fundamental transformation process is required. From a technical point of view, power becomes the dominant factor for the system design. Electrical grids have to be more dynamic and they have to be turned into smart grids. In order to manage volatility, not only electricity has to be considered. As most of the renewable energy sources are generating electricity this energy form will stay the energy hub, however, it has to be integrated into a holistic electricity, gas and heat system. As a consequence, the coupling of the industrial, mobility and building sectors will occur. Capital costs are replacing fuel cost. Thus finance becomes a pivotal element. Today's and future challenges for the energy system are discussed and solutions are proposed. The ongoing transformation process in the energy business shows disruptive characteristics. It is merging with digitalization which is another disruptive mega trend. It turns out that the legal framework that is guiding the transformation process of the system has to be adjusted to the new physical principles. Technology is available in principle and emotions of customers are getting an increasingly important factor.

Keywords: "Energiewende", system transformation, digitalization, renewables, power to heat, power to gas, demand side management, smart grid, smart market

1 Introduction

Today's electricity system has been designed and built through the last decades. It is based on big power plans with positions close to regions showing a huge electricity demand. Their efficiency is defined by the so-called "growth laws": The higher the power the higher the efficiency. These power plants use fossil or nuclear fuels with high energy densities. The generated power is controllable, the load flow follows the voltage levels in a top down direction and power frequency is the synchronizing quantity. From an environmental point of view, emissions like nitrogen oxides, sulfur dioxides, dust, mercury, heavy metals or noise are a big issue and require sophisticated filter technologies. Above all, coal and gas fired power plants emit carbon dioxide which leads to global warming and nuclear power plants bear immense risks which seem to be uncontrollable and which have already caused disasters like Chernobyl or Fukushima. The required and feasible alternative electricity system is based on small dispersed power plants using renewable energy sources like sun, wind, hydro or biomass. The energy density of these sources is rather poor and the availability is volatile and limited. This results in a high generation capacity which has to be installed. In addition, there is no full controllability of the main sources sun and wind. Only the reduction of generated power is possible. Electricity is fed into the lower voltage levels which turns the direction of the load flow from top down into bottom up. Combined with the occurring power peaks new grid designs and operational principles are necessary. Concerning the efficiency of electricity generation a new logic occurs. The growth laws are still valid, however, mass production, standardization, integration of generation into existing structures (like buildings) allow new methods of cost reduction. Fuel costs are replaced by fixed infrastructure costs. System stability can no longer be granted exclusively through frequency power control. Active large scale and online data exchange becomes an additional important means. In order to get the pronounced volatility of generation under control, demand side management and storage devices have to be included in the system. With respect to power-to-X technologies, like power-to-heat, power-to-gas, power-to-mobility, power-to-chemistry, the electricity sector gets much closer coupled with other energy forms and other economic sectors.

In order to describe the new energy system a sound understanding of the reasons for the system transformation, the system in place and the challenges of the incoming system based on renewable energy sources is necessary. Electricity generation and management of sources with pronounced volatility has to be analysed and aspects like efficiency, volatility and use of energy on the consumption side have to be discussed. After having developed a picture of the target structure the effective and efficient implementation process is in the centre of interest. Important aspects of the energy system of the future are the role of self-sufficiency, autonomous distribution grids and smart markets but also big data applications in energy systems. Finally, system design and quality issues, new technologies which will be available in the predictable future and which will offer new options for the system design as well as the interaction between technology and the legal framework which defines the economic base for entrepreneurial decisions have to be taken into consideration.

2 Basic considerations on a system based on renewable energy sources

The starting point for considerations on the future energy system is the question about the reason for the entering into a fundamental, long-term, challenging and even disruptive transformation process. The system in place is well functioning, efficient and reliable. It is one of the pillars of the national economy and based on big power plants using fossil or nuclear fuels. They are located in the load centres of the individual regions. The specific structure of the generation units defines the design of the electrical transmission and distribution grids.

Since unconventional exploitation technologies have reached technical and economic maturity, shale gas and oil as well as tight gas and oil are flooding the markets and leading to historically low energy prices. Reserves and potentials of natural gas and oil have been extended significantly. For hundreds of years there will be no shortage concerning their availability. Additionally, coal has to be considered as an energy carrier with an extremely long-term range. As a result, the availability of fossil fuels is no more - as assumed a few years ago – the bottleneck for the existing energy system which includes electricity, heating and cooling as well as mobility. On top fossil fuels are cheap.

The limiting factor, however, is the accessible capacity of the atmosphere for the absorption of carbon dioxide. The generation of this molecule is linked to the combustion of fossil fuels and the carbon dioxide concentration in the atmosphere has a substantial impact on the average global temperature. An increasing concentration means an increasing average global temperature. The emissions of carbon dioxide caused by human activities have already reached a level which has a visible and negative impact on the climate in the biosphere. Unfortunately, the carbon density, i.e. the focus on coal fired power plants has been strengthened within the last couple of years. It has become absolutely crucial to enter the global decarbonisation process of society, industry and economy immediately.

Today, there are several options available at different technical and economic maturity levels. Starting with the most developed option we have to mention:

- Use of renewable energy sources (RES) like wind, sun, geothermal, hydro, ocean streams
- Carbon capture and storage (CCS) technology supplemented by carbon capture and conversion (CCC)
- Nuclear circular economy (fast breeder technology and reprocessing of nuclear fuel)
- Nuclear fission (tokamak and stellarator technology).

Despite the fact that global warming has become the number one challenge for mankind, the entering into the global decarbonisation process and the start of the transformation of the fossil based energy system still requires to overcome some obstacles. The main challenge consists in the local divergence of:

- Origin of emission – Carbon dioxide emission is performed in country A
- Impact of global warming – Damages through climate change occur in country B
- Technical solution for decarbonisation – Availability of technology and option to export the technology are given in country C.

There is a need to overcome short-sighted national selfish behaviour and to take common responsibility for the protection of the biosphere. The implementation of a global greenhouse gas management and emission reduction scheme is necessary. Politics has to find a swift answer concerning the current divergence of national interests. The recently adopted United Nations Framework Convention on Climate Change shows some promising progress concerning this issue [1].

The handling of externalities is one of the key factors for the solution. The economic logic applied by companies, by individual nations and on a global level differs. Externalities are not sufficiently reflected in the current market prices. Carbon dioxide emissions lead to much lower costs on a company level compared to the damages they are creating today or in the future on a global level. This disparity has to be abolished. Nevertheless, the entering into the national decarbonisation path by heading for a renewable and energy efficiency based energy system is indeed an investment intensive, however, not an altruistic process. The most important sources of fossil fuels are concentrated in a relatively small number of countries with partially instable political situations. Renewable based energy systems are using domestic sources. Due to this, they increase the independence from fossil energy imports as well as the cash flow to the exporting countries. Finally, the current low price level will not be sustainable and increasing prices for fossil fuels have to be expected in the future. Also the power plants themselves will get more expensive as increasingly severe environmental standards will require additional investment.

It is key to head for an efficient and effective target energy system and to optimize the transformation process. Due to this, it has to be distinguished whether the renewable energy sources to be used for the electricity generation are controllable (e.g. hydro and geothermal) or volatile (e.g. wind and sun). The higher the percentage of volatile and non-controllable source the more sophisticated the technical solution needs to be. As long as the percentage of volatile renewable energy sources does not exceed a percentage of 55 % to 60 % from a technical point of view, fast back-up power plants like gas turbines or combined cycle gas turbines together with demand side management – e.g. based on power-to-heat systems – are sufficient to achieve a stable and balanced energy system. Exceeding the 55 % to 60 % threshold of volatile renewable energy sources means the implementation of reversible long-term energy storage systems [2]. From today's perspective, power-to-hydrogen devices are a realistic option. Batteries are rather short-term and pumped hydro power plants are more mid-term storage technologies. It is important to note that the percentages mentioned are referring to the situation in Germany. Nevertheless, these facts allow the draft of a technological transformation roadmap. **Fig. 1** gives an overview.

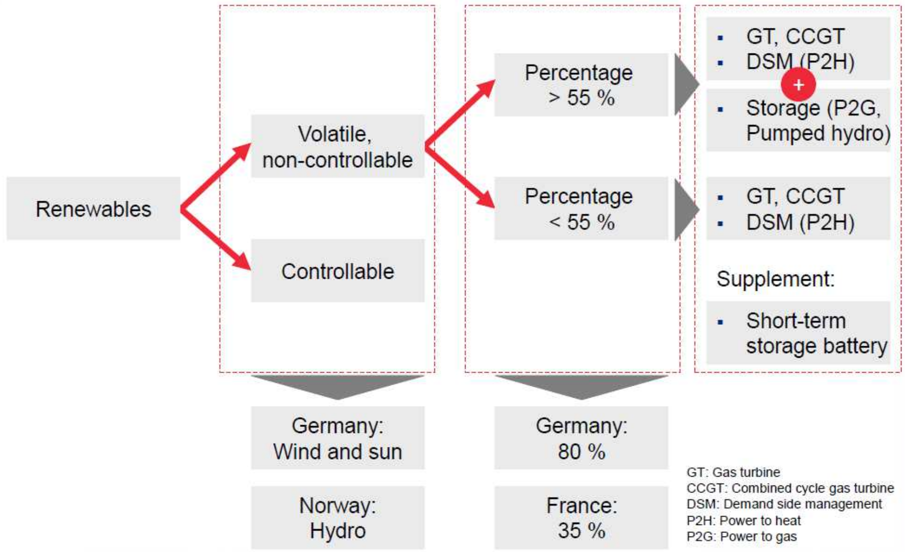

Fig. 1: Different structures of renewables and system architecture

German policy defined some additional conditions for the energy system of the future. The current "open" energy system based on fossil and nuclear fuels (without circular economy) shall be transferred into a "partially closed" system based on 80 % renewables by 2050. This includes the phasing out of nuclear and coal fired power plants, the focus on natural gas as the remaining fossil energy carrier, the extended use of combined heat and power plants (CHP) and the significant increase of energy efficiency on the consumer side. It has to be noted that still one step is missing in order to reach a "fully closed" energy system.

3 Electricity generation and management of sources with pronounced volatility

In order to achieve the 80 % goal of renewable based electricity generation, a substantial expansion of the installed capacity of renewables is a necessary precondition. In the case that the most important available renewable energy sources:

- are volatile
- have a low energy density
- have a low annual utilisation time
- have high power gradients
- are at places without generation in the past

the additional capacity of renewable energies amounts to the same level as the already existing conventional fuel based power plant capacity in order to achieve a percentage of the renewable based generation of 35 %. Additionally to the fact that therefore a huge surface is requested the conventional generation has to become the complement to the renewables based generation. It increasingly takes on the role of a highly flexible back-up with a significantly reduced operation time. Finally, the extension of distribution and transmission grids is necessary and also re-dispatching becomes an element of grid operation.

In Germany, within the next couple of years a percentage of 35 % renewable energy in the overall electricity mix will be achieved. The total installed power plant capacity will amount to more than 200 GW. The conventional power plants – gas fired combined cycle gas turbines (CCGT), coal and lignite fired steam turbines, combined heat and power plants – can change their offered power between about 30 GW and 90 GW. The lower value is defined by must-run power plants, due to system stability reasons but also due to heat generation in combined heat and power plants.

The power that can be consumed varies as well between about 30 GW and 90 GW. This leads to the situation that availability of sun or wind in times of low electricity demand will lead to a substantial generation surplus. This surplus has to be handled with respect to generation and demand balance but also power transportation by the grid.

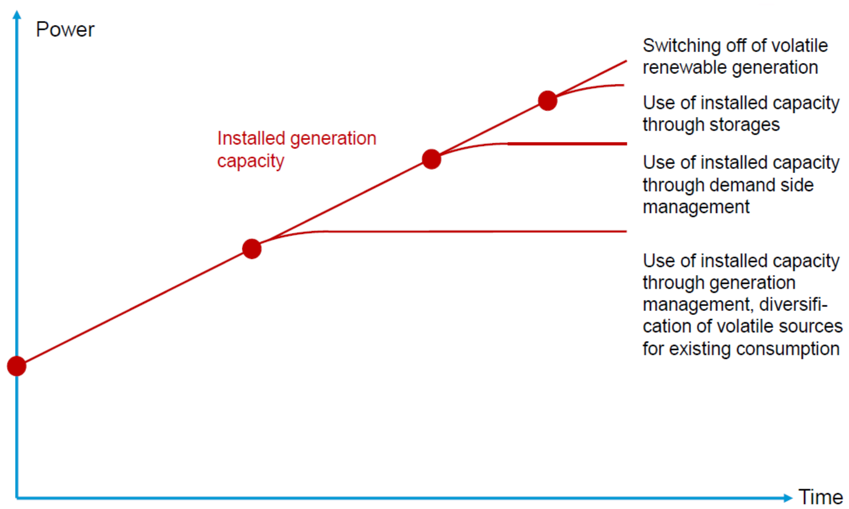

Fig.2 : Generation management, load management, storage but also switching off of surplus generation design the system

Regarding the German long-term 80 % renewables target scenario, hydro (4,900 h) shall contribute about 5 %, wind offshore (3,800 h) about 5 %, wind onshore (2,200 h) about 35 % and photovoltaics (1,100 h) about 35 %. 20 % remain for (flexible) combined heat and power generation (7,100 h).Taking the annual usage times of these energy sources in Germany into account, the total generation capacity that has to be installed amounts to about 400 GW. This is equivalent to 4.7 times of the maximum load and consists of about 100 GW controllable thermal power plants and 300 GW uncontrollable renewables. This capacity does not include the potential demand for power plants only used for stabilizing the system (e.g. peak power plants exclusively used for re-dispatching).

The renewable energy mix in Germany shows a certain diversity with respect to type and location of sources. This leads to a more balanced and more continuous generation pattern. Available real data show that the simultaneously maximum available power of renewable energy sources P_{max} is equivalent to about 50 % of installed capacity P_{inst} [3, 4]:

$$P_{max} \approx 0{,}5 \cdot P_{inst}.$$

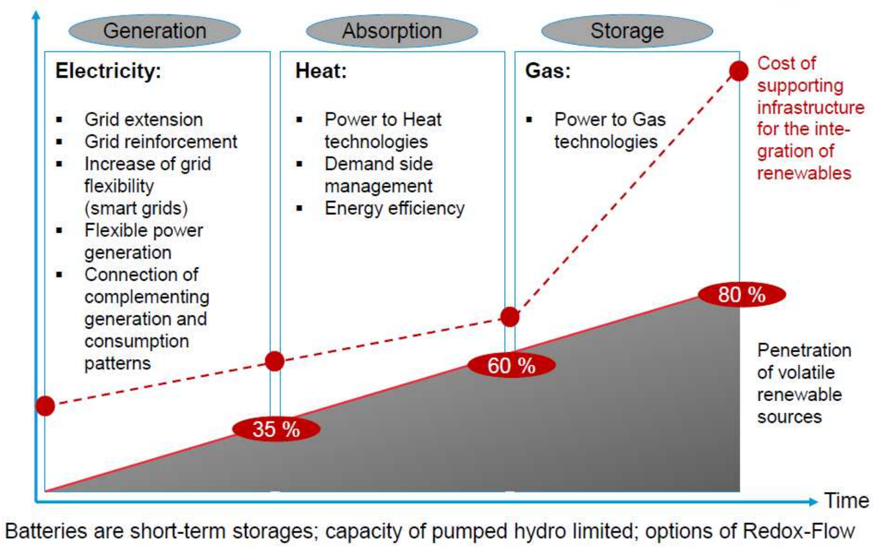

Fig. 3: Grid extension, demand side and generation management are less expensive than storage systems. This defines the penetration path of technologies

As a consequence, in an extreme case about 180 GW = 30 GW + 150 GW of generation capacity have to be handled even at times where the demand amount to about 30 GW. This requires the implementation of conversion and storage technologies. Mechanical storages, like pumped hydro, are very mature from a technical point of view, however, the amount of stored energy is limited and also suitable places for their establishment are limited. The energy densities of thermal and chemical energy are much higher and they are much more flexible with respect to appropriate locations. Power to heat (P2H) and power to gas (P2G) devices are in the centre of interest. Batteries are a supplement which is rather a short-term storage system. Today, typically units up to 50 MW are in operation. As a matter of last resort also curtailing should not be excluded. **Fig. 2** shows the principles of handling the challenge of the necessary overcapacities.

Power to heat technologies are very mature, have relatively low specific investment and high operational efficiencies up to 99 %. There are two basic versions. The first one is an electric boiler shaped as a tube where pressurized hot water (with e.g. 105 °C) is injected, the temperature is increased by another 5 K to 10 K and the water is then directly delivered to the district heating system. It is possible to provide dynamic (positive and negative) control power as well as operate the device in the steady state mode in case of midterm energy surplus. Typically, installed power amounts to 10 MW or 20 MW.

The second version is a thermal storage which consists of an insulated tank filled with hot and pressurized water. Such a storage can be charged or unloaded with about 50 MW up to 30 h to 40 h. Storages operating with higher pressure and temperature are smaller and typically used as hour storage. Two layer stratified storage tanks are rather used as day storages and operate with lower pressure and temperature. Their size can be enormous (e.g. 30 m diameter and 70 m height). The storage is loaded either through steam from the turbine or through an electric boiler. It is unloaded by injecting the heat into the district heating system.

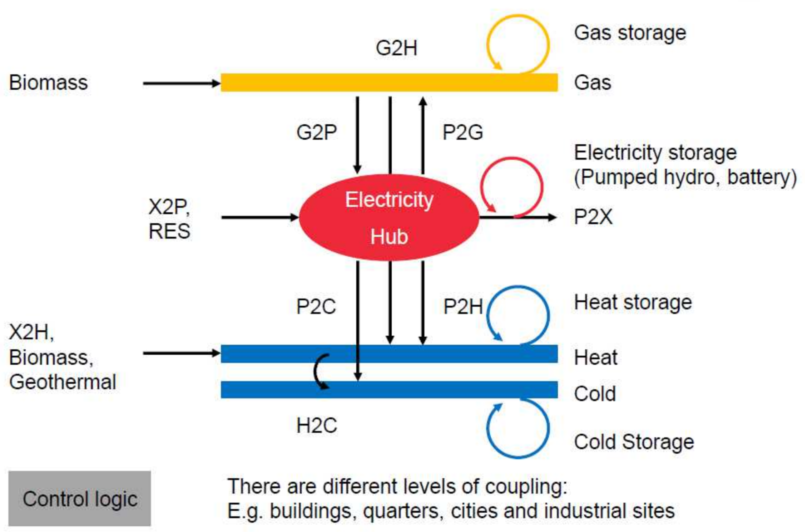

Fig. 4: The future energy system is based on the coupling of energy carriers on different levels. Electricity is the hub

Primarily, power to heat devices are demand side management tools and not reversible storages. However, taking the fact into consideration that renewable surplus electricity is used for the heat generation instead of gas, it is possible to regard this process from an energetic point of view as an indirect transformation of electricity to methane and thus as an indirect storage system.

Power to heat shall be used as a general term. It includes also technologies like heat pumps or small electric heaters in domestic heating systems. Furthermore, cooling by means of compression or absorption machines is considered as an element of this technological area too.

Power to gas consists of two basic steps. First, an electrolyser splits water by the use of electricity and a membrane into oxygen and hydrogen. Second, in a catalytic process hydrogen reacts with carbon dioxide to methane. Both steps are energy consuming and the provision of pure carbon dioxide has to be managed as well. Today, only for the first step partially mature technical solutions exist and the first large scale devices with a power of several MW are in operation. The proton exchange membrane (PEM) technology is quite robust, allows high load gradients, an operational range from 0 % to 120 % of rated power at an efficiency of about 80 %. Electrolysers need more than 10 times higher investment compared to power to heat. Improvement of materials and scaling up of production figures shall lead to an investment reduction of a factor 3 in the predictable future. This will make electrolytic produced hydrogen competitive with the steam reformation process which is the current standard method for hydrogen production. In order to use hydrogen as a reversible chemical storage that is in the position to compete with natural gas a reduction of the specific investment by a factor 10 to 15 is necessary. This is a challenge, however, it seems feasible to achieve this target within the next decade.

Hydrogen can be directly injected into the natural gas system. A concentration of 5 % to 10 % must not be exceeded. Therefore, an appropriate control system has to be installed. Nevertheless, this is a feasible approach with limited needs for investment. Additionally, the second step to produce methane increases the investment and costs of the energy transformation process substantially. The overall efficiency is reduced significantly. From today's perspective it is questionable whether the second catalytic step will be required to a larger extent in the future.

The technical facts described above clearly indicate three phases of the German "Energiewende". The first phase up to 35 % of volatile renewable energy sources can be called the "phase of electricity". Reinforcement of transmission and distribution grids, increase of grid flexibility (smart grids), fast conventional back-up power plants are building the technical scenario. At the latest in 2020 this percentage of volatile renewable energy sources will be exceeded. Demand side management (DSM) becomes increasingly important. One very effective and efficient method is power to heat in its wider sense. Therefore, this phase can be called "phase of electricity and heat". From today's perspective at the latest 2030 at about 60 % of volatile renewables in the electrical grid, reversible long-term storage becomes necessary. Power to hydrogen seems to be the appropriate technology. The "phase of electricity, heat and gas" will start.

The successive coupling of different forms of energy allows to use the existing infrastructure in a new and modified was and offers the time to develop the technology in such a way that economic solutions are available at due time. Additionally, the work on energy efficiency has to be continued.

Electricity will be the energy hub as most of the renewable based generators offer electricity as an output. The coupling with heat and gas allows the control of the pronounced volatility in the electrical system. **Fig. 3** shows the penetration path of technologies and **Fig. 4** the design of the future coupled energy system.

Next to the coupling of energy forms, there will be a new and more intensive coupling e.g. of the industrial sectors energy, chemistry and mobility. Hydrogen produced by electrolysis will be used in the chemical industry or there will be electric vehicles.

4 Efficiency, volatility and use of energy on the consumption side

The voltage challenge will not only occur on the generation but also on the consumption side. Electric driven heat pumps or air condition systems as well as electric vehicles are high power consumers. Driving all cars in Germany electric will increase the demand of electrical energy by about 15 %. However, concerning the power demand the situation is totally different. Assuming a maximum power demand in Germany of about 80 GW and comparing public high power chargers for electric vehicles with 40 kW gives the result, that about 2 million cars (5 %) out of 40 million could be simultaneously charged. In this case, no other electricity consumption would be possible in Germany. Limiting the total charging power to 8 GW (10 % of peak demand power) reduces the number of simultaneous charged cars to 200,000 which corresponds with 0.5 % of all registered cars in Germany. These figures clearly indicate that the large-scale roll out of electric vehicles without a smart charging concept with power control is not possible.

Form an energy point of view through efficiency increase the demand of fossil fuels for heating and mobility will be reduced significantly in the next decades. The electricity demand, however, will stay more or less constant. Of course, there is efficiency increase in the electricity sector but also non-electric applications of today will use electricity tomorrow and additionally the digitalisation increases the demand of electrical energy.

The use of flexibility in the existing commercial and industrial production structures becomes increasingly important. This can contribute in a substantially to the stability of the electrical system. Demand side management is one of the fields, where the “Energiewende” and digitalisation are merging. Sensors provide real time data of the consumption of the production site. The information is transmitted through a secure channel to the web cloud. Here data analysis with the help of big data algorithms takes place. In combination with a simulation model of the production site and a neuronal network, a forecast of the consumption and the flexibility options can be derived. The result is transmitted to the production site where the flexibility options can be used to optimize the energy demand according to the market situation. Additionally, adaptive learning algorithms have to be applied. The neuronal network has to be trained by taking the process adjustments based on the forecast into consideration.

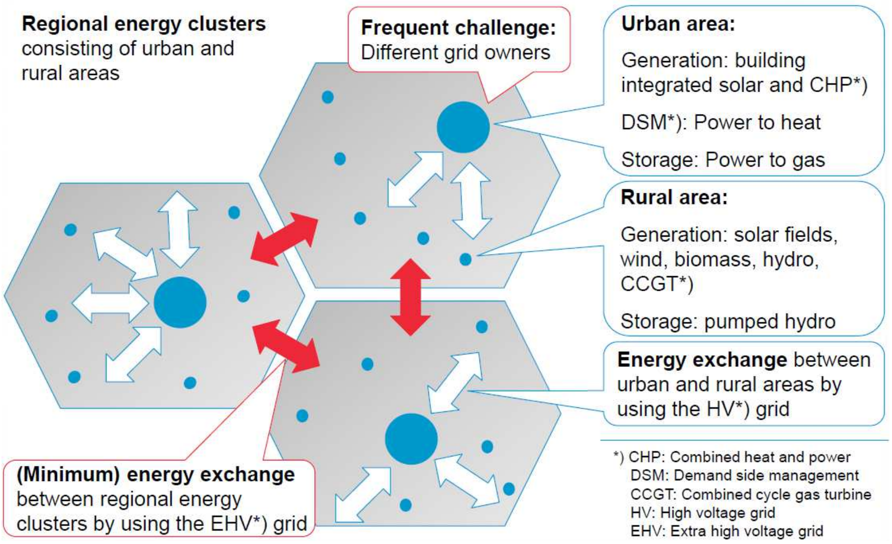

Fig. 5: System of the future and the principle of subsidiarity. Combining different patterns on a modular base in order to cope with volatility

After the periods of Energy 1.0 (traditional generation), Energy 2.0 (huge off-shore wind farms), Energy 3.0 (mid-size on-shore windfarms, combined heat and power plants, solar farms) we are entering Energy 4.0. The generation of electricity becomes more decentral and penetrates into consumption sites. Building integrated photovoltaic, decentral batteries and other modern technologies make the so-called "Prosumer" become a reality. This increases the data exchange even more and supports the digitalization of the "Energiewende".

5 Effective and efficient implementation structures of the new energy systems

First, the "Energiewende" means the technical control and system integration of decentral, volatile and high power electricity sources into the energy system in an efficient and effective way. Second, the economic challenge is the transformation of a system based on capital and fuel costs into a system that mainly consists of capital costs. Investment needed in order to establish the future energy system has to be kept as small as possible. There are some basic principles which support this target:

- **Principle of technical subsidiarity**

In order to connect and integrate diverse structures into one system a modular design is the appropriate solution. Energy cells in Europe are buildings, quarters or villages, cities, regions, countries. They have to be connected through lines. The energy exchange between two neighbouring module has to be reduced to a reasonable and economic extent. The power balance should be achieved as far as possible within one module. Regional energy clusters consisting of the integration of urban and rural areas with the help of the high voltage grid are of specific interest. When designing the modules, the law of Pareto has to be taken into consideration. **Fig. 5** explains the modular concept.

- **Principle of technical diversification**

A number of individual volatile elements are stabilized through diversification. The combination of different generation and consumer patterns is more stable compared to a homogenous set-up. The higher the percentage of volatile renewables within the generation mix the less important becomes the maximization of generated energy and the more important the stability and reliability of generated energy. Due to this, the need for storage can be minimized. Diversification is possible with respect to technology and location. **Fig. 6** shows the time depending importance of maximum generation and power balance.

- **Principle of technical modification**

Using and supplementing existing infrastructure in order to support the "Energiewende" minimizes transformation costs and thus has a direct and positive impact on the economy of the "Energiewende". Examples are the use of district heating systems as energy buffers and demand side management options or smart grids, where the addition of information and communication technology (ICT) allows to extent the transport capacity of existing grids.

- **Principle of multiple use of assets**

  The use of one asset for different purposes helps to reduce the investment volume as well. E.g. a domestic battery can support the self-sufficiency of the building, the voltage stability in the grid, the power balance in a balancing group or the power frequency control. Superimposed control loops are key in order to implement this principle.

Every single-sided solution, e.g. fixing the whole challenge on a European level, could work from a technical point of view. However, it will not be the economic optimum. It also has to be mentioned that a technical optimum as a rule is a broad optimum which makes several target scenarios feasible.

6 The role of self-sufficiency

The individual energy cells shall be self-sufficient to a reasonable extent. As an example, a private home with a 4 kWp solar panel on the roof top in Germany generates about 4,000 kWh electricity per year. This corresponds with the annual electricity demand of one family. With respect to power the self-sufficiency amounts to about 30 %. This means in 30 % of the time there is no exchange of electric energy with the upstream grid. A battery with about 5 kWh of stored energy will raise the autarchy level to about

60 %. The further increase of self-sufficiency by 10 % requests to double or to triple the installed battery capacity [5]. Such a target is fully out of the economic scope.

Active energy apartment buildings achieve with today's technology autarchy levels between 70 % and 80 %. They produce about 20 % more energy than they consume. The advantage compared to private homes is based on the divers consumption patterns of the numerous families living there. Technologies used are amongst others roof top solar panels, building integrated solar cells, battery, waste water heat pump, excellent thermal insulation and hot water heat storage. In expensive urban these buildings are showing even today rental fees for the flats that are fully competitive. As a rule, the rental rate is an all-inclusive rate and includes a heating, electricity and mobility package. Only the surplus consumption of electricity is billed. The mobility package includes the use of electric vehicles [6].

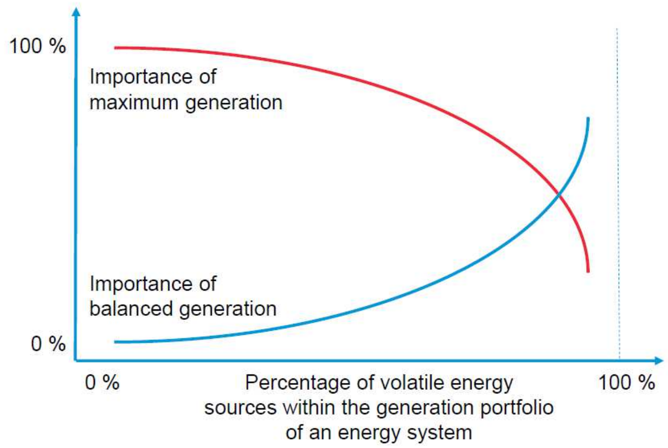

Fig. 6: Changing technical targets. The roles of maximum and balanced generation

Despite of this significant progress in the domestic sector it has to be taken into consideration that the transitional period in order to transform all of the existing buildings into buildings with the features described will take several decades. Additionally, regarding the overall picture, today's energy use for mobility shows the same order of magnitude as the consumption of electricity while the energy use for heating is roughly twice as high. With respect to electricity, private households consume about one quarter whilst three quarters are consumed by industry, services and commercial activities. This clearly shows that the implementation of the "Energiewende" needs a holistic approach with specific, however, coordinated solutions. As described, "Energiewende" on a domestic level will focus on very decentral components like solar panels and batteries. On the contrary, industrial sites will show an overall self-sufficiency level which is much lower. Through the medium or high voltage grid the will be much more involved in the energy supply of the region concerned. Wind and solar farms, CHPs, power-to-heat and power-to-gas devices are the requested technologies.

7 Autonomous distribution grids and smart markets

Renewable energy sources are installed at places where so far electricity generation did not take place. Additionally, the sources are powerful and extremely volatile. This creates new challenges for electrical grids.

The transmission grid has to be reinforced in order to allow the implementation of the principle of diversity. Above all, the bottlenecks between the Northern and the Southern parts of the country have to be overcome. Traditional static solutions (new AC or DC lines) but also dynamic solutions (fast and flexible peak power plants combined with demand side management) have to be taken into consideration. The question whether re-dispatching is the exemption or the rule has to be discussed. The more self-sufficient the regional energy clusters are the less reinforcement of the transmission grid is needed. The increase of horizontal load flows supports regional autarky.

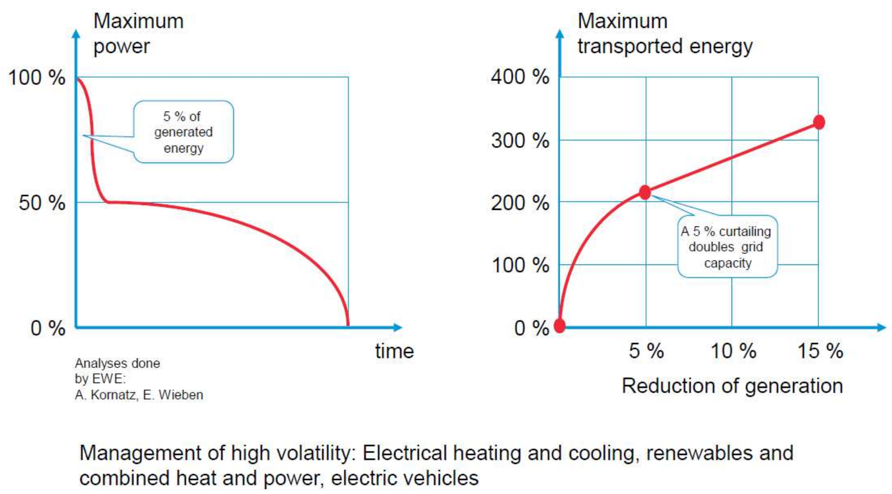

Fig. 7: Curtailing maximum power by 50 % doubles grid capacity and reduces generation by 5 %

The distribution grid has to be extended in order to connect the new renewable energy sources. This reflects the fact that 95 % of the renewable base energy generation is fed into the distribution grid. The strong link between the volatile and decentralised renewable energy sources and the distribution grid has two main consequences.

The first one is that 95 % of the transported energy requires 50 % of the installed grid capacity. The remaining 5 % of the energy request the other 50 % [7, 8]. This pronounced asymmetry leads to the idea of a smart distribution grid. If it is possible to influence the decisive 5 % of the energy demand the total transported energy can be doubled at low investment. Smart grids are linked to grid supportive demand side management and they reduce through these interventions the power quality to a limited extent. The right balance between quality reduction and capacity increase with low investment has to be found. **Fig. 7** and **Fig. 8** are demonstrating these considerations

The second consequence is that smart grids need information about the voltages at nodes and currents in branches. Regarding today's low and medium voltage grids, this information is not available. The most detailed information are current and voltage at the starting points of main lines in HV / MV substations (online), possibly the maximum current within a certain time period of MV / LV transformers (offline) and the metered annual consumption of customers (offline). The current grid design assumes a top down load flow from a central source to a decentral customer. This precondition is no longer valid. Today, as a consequence, voltage increase in the grid may occur without any notice of the distribution system operator.

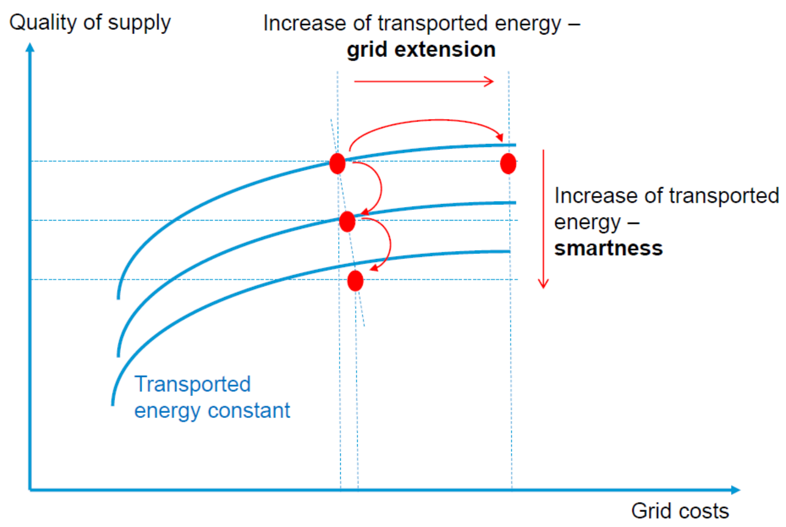

Fig. 8: Economy of a smart grid is based on the balanced between grid extension costs and quality

Smart grids are an answer to this development. They consist of several voltage and current sensors in suitable places in the public grid. The voltages of all phases and the currents of all phases including the neutral are measured. The data are transferred (e.g. through power line carrier technology) to the smart controller situated in the transformer station (low voltage smart grid) or substation (medium voltage smart grid). In the smart controller based on static grid topology data (from the geographical information system of the distribution system operator) a state estimation algorithm is calculating per phase all voltages in all nodes and all currents in all branches. This structure allows to minimize the number of voltage and current sensors. Typically, the necessary number of sensors is below 10 % of the number of connection points. In case, the smart controller is detecting an infringement of the voltage band or an overcurrent it can react based on the available options.

Grid centred measures like voltage controllable transformers, voltage controllers in lines or reactive power controllers allow to compensate above all voltage band infringements which account for about 80 % of all necessary interventions. Additionally, there are customer centred measures which consist of reactive power influencing and active power influencing actions. As a rule, only active power influencing actions have an impact on the customer supply quality. They have to be used as a matter of last resort.

Smart grids allow the use of the grid inherent capacity reserves and increase the utilisation of the installed primary components, however, they also cause a certain reduction of supply quality. At a given supply task a weak primary infrastructure is causing more interventions of the smart grid compared to a strong primary infrastructure. Therefore, at a given primary infrastructure and an increasingly complex supply task the number of interventions is increasing as well and the supply quality is reduced. The balance of delayed or avoided grid reinforcement and supply quality has to be kept. This question defines the limits of smart grids.

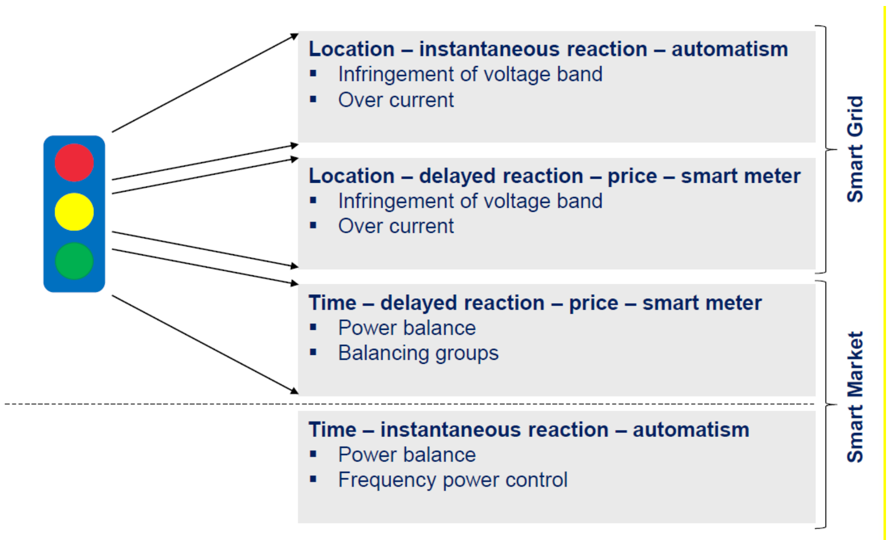

Fig. 9: Smart grid and smart market. Autonomous elements and price signals

Medium voltage smart grids use low voltage smart grids with their transformers as sensors but also as actors. The smart controller of the low voltage smart grid receives its orders from the smart controller of the medium voltage smart grid. Other actuators are switches, reactive power controllers, the voltage controllable HV/MV transformer and last but not least medium voltage customers. Matching boundaries of medium voltage grids is one of the strategies that supports the optimum use of medium voltage primary infrastructure.

Smart grids and smart markets have to work in correlation. To begin with, the smart grid forms the platform for smart markets. Smart markets intend to balance electricity offer and demand on a 15 min base through price signals. They are a time-based and voluntary issue. Power frequency control is fine-tuning the balance below this time period on an automated base. A smart grid in the green phase is just supervising the behaviour of electrical sources and sinks participating in the smart market. If an infringement of the voltage band or the rated current of a specific component is identified the smart grid is in the red phase. Instantaneous, automated and self-sufficient action is required. Suitable actuators are addressed directly in order to bring the system back to the popper operational mode. In the red phase smart grids are a location-based and compulsory issue. There can also be a prior yellow phase where the distribution system operator intends by means of grid tariff adjustments on a 15 min base to motivate customers on a voluntary base to adjust their consumption or generation. It is important to note that the legal framework for such a system is not in force so far. **Fig. 9** gives an overview and [9] offers deeper insights. **Fig. 10** demonstrates the corresponding change of the tariff structure. Energy in general and above all volatile energy is loosing importance, while system management and stability measures will dominate the future electricity bill. As a consequence, a new type of competition has to be implemented and replace the current energy-only-market.

8 Big data applications in energy systems

Smart grids are assembling a huge amount of grid based data. Even without actuators a real time monitoring of free grid capacities is possible.

A proper set of sensors allows the calculation of all voltages and currents in all branches and nodes. If some additional and optional sensors are installed a check of the calculated values becomes possible. The deviation of calculated and measured value at one point of the grid means as a rule a difference between the grid topology which is used for the calculation and the real grid topology. Based on this, e.g. open switches but also single-phase interruptions can be identified. Smart grids become an instrument to supervise the reliability of the grid. Furthermore, the asset condition can be evaluated. E.g. the damping coefficient of the power line carrier signals allow the evaluation of the insulation quality. Big data analysis tools enable the identification of correlations without full understanding of the causality. Adding other data, like whether, time, weekday and others, should allow to establish a congestion forecast and to take preventive measures in order to avoid a congestion. Again, the legal framework is not available for the implementation of such features.

9 Further technical challenges

The “Energiewende” is focussing on the large scale integration of powerful and volatile electrical sources at places where no generation took place so far. Extension and reinforcement of transmission and distribution grid is necessary. However, also increase of grid flexibility by using the concept of smart grids is required. The “as if” static balancing of generation and load fluctuations on a 15 min base is a second challenge which is addressed by new power market models. As soon as the huge central power plants are phased out the spinning reserve is reduced and the dynamic balancing of the power system becomes an issue. New devices like fast reacting batteries have to support the power frequency control. Appropriate concepts are currently developed.

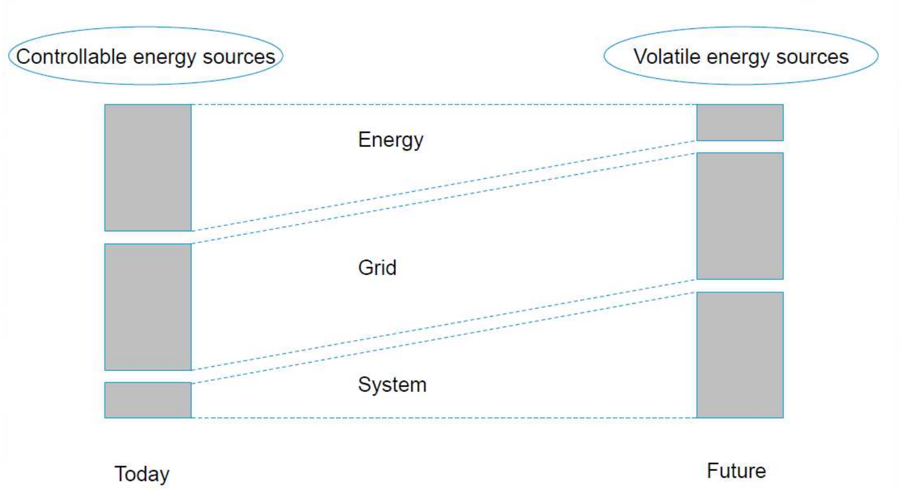

Fig. 10: Tariff structure of the future

In distribution grids the load flow might change due to many new power generators in the lower voltage level. This is an issue for the protection system. Additionally, the voltage becomes more volatile. Due to the reduction of number and installed capacity of the huge central power plants the overall short circuit is reduced as well. This has an impact on the overall voltage quality, the impact of flickers, harmonics and dips. The grid becomes weaker. The contribution of the new dispersed generators is rather low as most of them are connected through electric converters to the grid. Also the role of fuses has to be reconsidered. Furthermore, the implementation of smart grid technologies leads to higher energy transports with the same primary infrastructure. The precondition is an active peak power management. In summary, these developments require an adjustment of grid design and operation principles.

The transformation process of the “Energiewende” will also lead to the penetration of new generation technologies like solar cells based on organic materials or perovskite crystals. Diversity of generation increases autarky. Cheaper Li-ion batteries and new storage options like improved super capacitors are additional options. As a result, the domestic sector will be rather self-sufficient and imbedded in pronounced decentralized structures. **Fig. 11** gives an overview about the mainstreams of generation technologies.

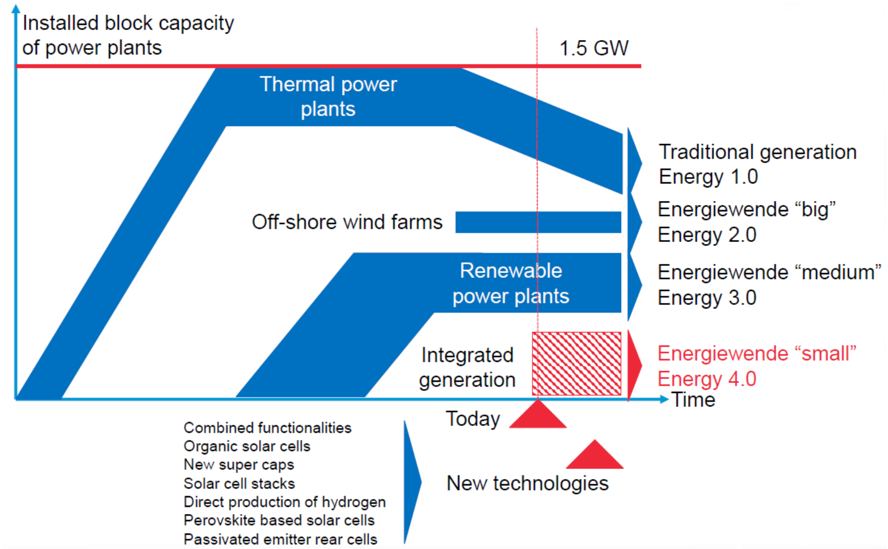

Fig. 11: The upcoming decentral "Energiewende"

The supply of industry requires different design. Combined heat and power plants, power to heat and power to gas devices but also on energy deliveries through cables and lines from the grid will be used. The electricity will be generated in wind or solar farms but also in central gas fired power plants. The industrial sector will be imbedded in the regional grid and generation structures.

Finally, the voltage quality issue has to be reconsiders. Cheap power electronics allows to set power quality individually at the grid connection point of the customer. Broader voltage bands in the grid would allow the transportation of higher loads with the unchanged infrastructure. The question what level of global and what level of local quality we need has to be discussed.

10 Summary and conclusions

The "Energiewende" is focusing on decarbonisation and means a global chance and a fundamental transformation of the energy system with a strong impact on society, industry, mobility, finance and infrastructure. A top down structure is turned into a bottom up one. Vertical load flows are replaced by horizontal ones. Fossil fuels are phased out and renewables become the backbone of the energy system of the future. This process has disruptive characteristics and the changes in the energy business can be clearly observed.

Digitalisation is a second mega trend. The gathering and availability of information, the interconnection of data hubs allows a new way of live and offers new opportunities for production, mobility and logistics. 3D-printers even allow the materialisation of data at any place on this globe. Through open source software intellectual property gets a new meaning and big data analysis tool allow the identification of new interdependences. Also this trend has disruptive characteristics.

A decentralized and dispersed energy structure needs coordination. Therefore, the "Energiewende" is merging with digitalisation. The result is disruption squared.

With respect to the decentralized energy system which is based on volatile renewable energy sources, in principle all required technologies are available. This includes generation as well as load management and storage. Of course, still there is a lot of work with respect to standardisation, optimisation, mass production, roll out and control, however, its mainly a coordination and management task. It has to be clearly highlighted that the current legal framework is not suitable to foster the implementation of the technology needed. In many laws and directives inherently the former centralized energy system still exists. Laws and taxation principles have to be reconsidered with respect to smart grids, storages and demand side management. Power to heat and power to gas devices have be considered as "energy converters" like a transformer and from an electricity centred system we have to progress to an energy, i.e. electricity, heat and gas, centred system. Finally, the decarbonisation process which today is defined for utilities and industry has to be extended above all to the mobility and building sector. The government should embellish the cap and trade principle and the market should identify the most economic and appropriate solutions.

In order to summarize, policy makers have to work on the legal framework for the transformation of the energy system. In this context, they should not forget that the "Energiewende" is standing at the threshold to turn form an economic and rational driven process to a consumer and emotion driven issue. Prices for solar cells and batteries have become so low that the desire for own generation units and the feeling of independence becomes the decisive element. Perhaps the "Energiewende" will be a self-running issue soon.

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