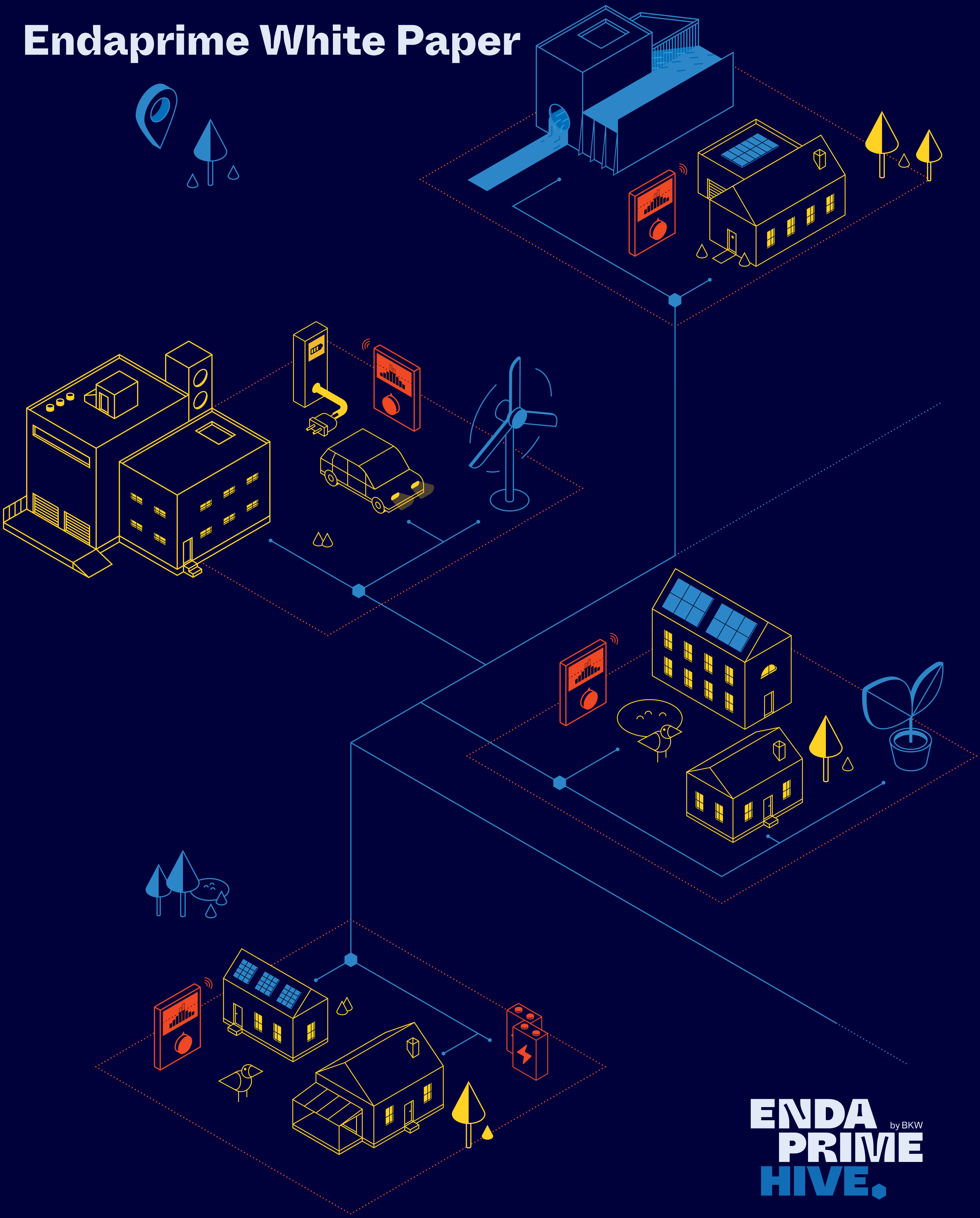
Energy cells as the new energy reality

Endaprime White Paper



ENDA PRIME HIVE by BKW

BKW Energie AG
Viktoriaplatz 2
3013 Bern
Switzerland

www.endaprime.ch
endaprime@bkw.ch

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Endaprime™

With the rapid growth of renewable energies and the decarbonisation of entire areas of daily life, the issues of energy, infrastructure and buildings are converging. The planning and operation of these systems are becoming complex, interdisciplinary tasks that require support through simulations and analytics. BKW's technology and innovation hub – Endaprime – is developing solutions for this new reality.

HIVE™

HIVE from Endaprime simulates the energy system of tomorrow in an intuitive, interactive way. It demonstrates the impact of expanding renewable energies and the electrification of mobility on the distribution system, energy self-sufficiency and environmental pollution. HIVE makes expert knowledge something that can be experienced and understood: complex connections are presented in a comprehensible way, thereby enabling a factual discussion about the energy system of tomorrow.

Management summary

Fundamental challenges in the energy system are becoming increasingly visible: electricity production is becoming more decentralised, system complexity is increasing, electricity grid capacities must be adjusted for the new realities and conventional end customers are transforming into active "prosumers". Endaprime is already tackling these challenges by coordinating and optimising the energy supply and demand at a regional or local level (e.g. buildings, districts, villages or municipalities) in order to achieve the ambitious energy and climate goals of the Federal Council.

As obvious as the energy goals seem at first glance, their effects are highly complex and diverse. This White Paper uses HIVE™ results to show how the energy and climate goals will impact the local energy system. The White Paper also proposes an approach with which the major challenges can be overcome: Endaprime takes up the practical approach of cellular energy which heralds a new turning point for the Swiss energy system with local automation and distributed intelligence.

2021: The energy transition is under way

Switzerland is currently in the middle of the greatest change in the history of its energy system. The starting shot for a net zero energy future has been fired, opening up a new chapter in Swiss history:

Decentralised electricity production overtakes traditional electricity production

Since 7 July 2021, the largest distribution system in Switzerland, that of BKW, has had a greater amount of installed PV capacity (276 MW from 13,540 systems) than hydroelectric power capacity (272.8 MW from 191 systems). Up to ten further photovoltaic systems are added per day.

With the phasing out of nuclear energy and the promotion of production from renewable energies, the few central production facilities that belong to a few energy companies and are largely connected to the higher voltage levels of the electricity grid are being replaced by numerous (often very small) production facilities, belonging to a large number of mostly private owners and usually connected to the periphery of the distribution systems (lowest voltage level). Before the reactor accident in Fukushima, only 6,500 photovoltaic systems were connected to the electricity grid in Switzerland. Ten years later, there are over 112,000 systems (SFOE 2021) which cover around 5% of current electricity requirements (Swissolar 2021). Installed PV capacity has only increased significantly in recent years since the first photovoltaic system in Switzerland was connected to the grid in 1982 (see Figure 1).

The expansion of decentralised electricity production is not shaped by the same business and economic considerations that apply to capital-intensive central electricity production facilities of the energy suppliers. Socioeconomic (e.g. income, technology adaptation, ownership, public funding) and socio-geographic (suitability for production or local experience) factors shape the investment decisions of the new energy producers. As a result, the expansion of decentralised electricity production varies greatly from region to region and even locally (Müller and Trutnevyte 2020, EnergieSchweiz 2021). The following relevant production tendencies become evident:

- Countless small and decentralised production facilities instead of a small number of large power plants
- Fluctuating electricity production instead of controllable electricity production
- Electricity production in the distribution system instead of in the transmission system

Decarbonisation leads to greater and “new” electricity consumption

Along with the shift in electricity production, changes to electricity consumption are also becoming more significant. Never have so many heat pumps been sold as in 2020. According to the Professional Association for Heat Pumps in Switzerland, over 28,000 heat pumps were sold in 2020 (FWS 2021). This corresponds to a 50% increase in sales compared to as recently as 2010. The electrification of the heating sector leads to greater electricity demand and new consumer profiles, particularly in the cold winter months.

However, the electrification and decarbonisation of mobility is the true game changer. Sales of electric vehicles achieve new records every year. While battery-powered electric cars accounted for just 1.7% of new registrations in 2018, by June 2021 this number had already risen to 14.3% (Roadmap Elektromobilität 2021). In just a few months, Swiss roads saw eight times as many plug-in vehicles. The adoption of electric cars depends on many factors, thereby resulting in regional differences with regard to the amount of electric vehicles as well: while in July 2021 the electric vehicles

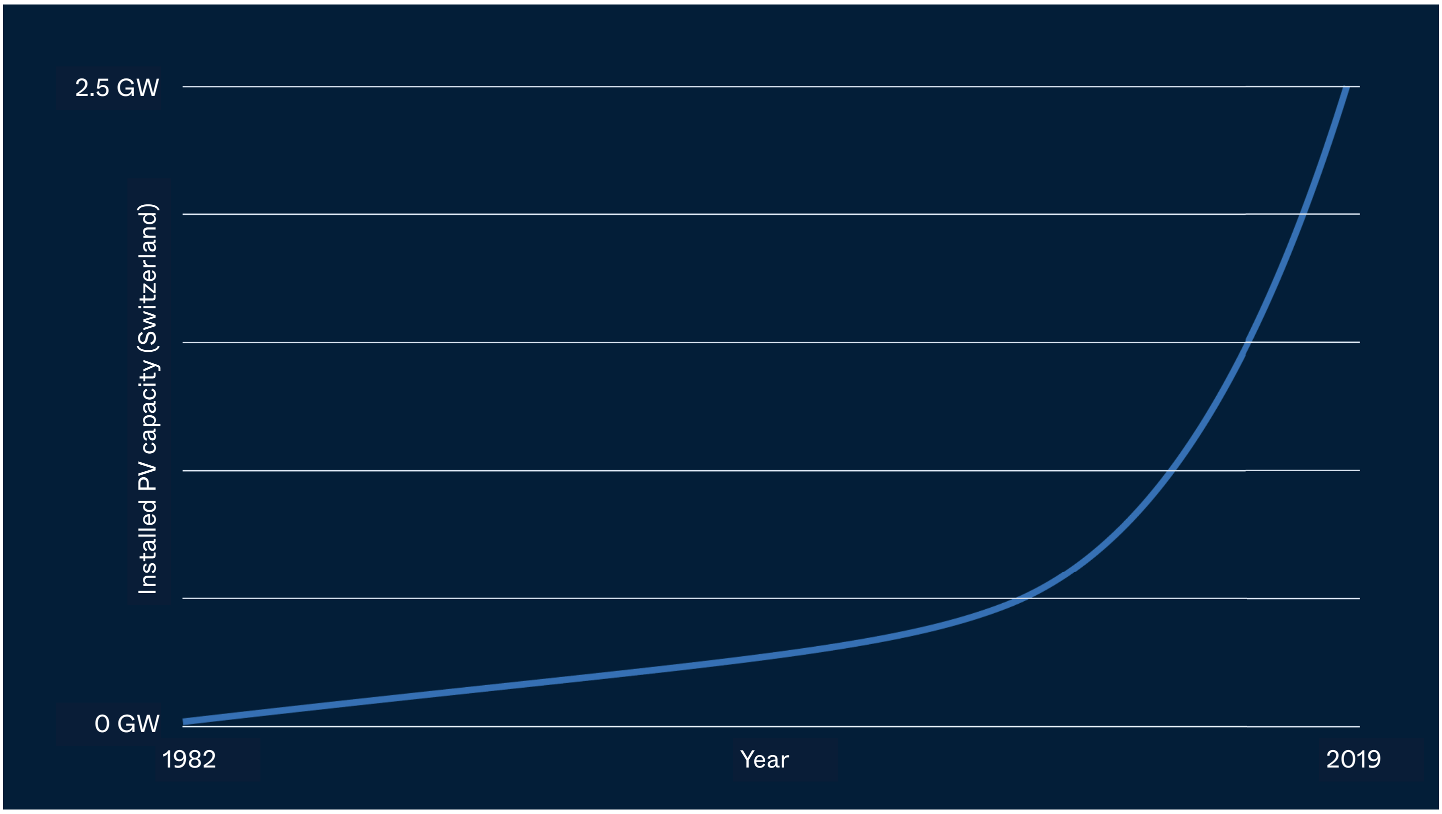

Figure 1: Trend of installed PV capacity in Switzerland. In accordance with (BFE 2021, BFE 2020)

in two Bern municipalities accounted for almost 5%, they accounted for less than 1% in 75 municipalities (ASTRA 2021).

The electrification of the mobility sector leads to an increased demand for electricity and power, and individualises the consumption pattern of households. Until now, representative statistical methods had sufficed for modelling the electricity and power requirements of conventional end consumers. However, since the mobility behaviour and thus the charging and discharging behaviour of electric car owners varies, previous consumption models must be reassessed. Among other things, electricity grid planners now have to include mobile loads instead of just stationary ones in their calculations. The following relevant consumption tendencies are becoming evident:

- Increased instead of decreased electricity consumption in households
- Individual instead of standardised consumption patterns

These tendencies will grow in coming years and trigger a profound change in the value chain. The changes are occurring gradually and slowly stripping away old principles. The future of energy becomes somewhat more tangible with “Energy Perspectives 2050+”.

2050: A net zero energy future

At the end of 2020, the SFOE published the “Energy Perspectives 2050+” which use current outline data and technology developments to illustrate the various different paths toward a renewable and climate-neutral energy future (SFOE 2020). The “Energy Perspectives 2050+” make up the official forecast and establish a certain planning foundation for the energy system of 2050.

The clear measures and targets in the areas of electricity production and consumption require fundamental adjustments which show the effects of the measures and the scope of these targets in a more impactful manner. The following changes result from the “Energy Perspectives 2050+” at the outset:

Changing electricity production to hydropower and renewable energies

- As a renewable, socially acceptable and low-CO_2 alternative to previous forms of electricity production, the importance of photovoltaics will greatly increase when it comes to advancing the decarbonisation of electricity production. By 2050, climate-neutral Switzerland should produce 40% of its electricity, i.e. around 33.6 TWh, via photovoltaics (currently 2.2 TWh). This corresponds to a 15-fold increase in the installed output of 37.5 GW (currently 2.5 GW). To date, around 0.3 GW of PV capacity has been installed every year. However, in order to achieve the energy and climate goals, five times as much PV capacity would need to be installed each year. The plan by SP National Councillor Roger Nordmann even assumes 50 GW, which corresponds to a 20-fold increase in installed capacity (Nordmann 2019).

- Hydropower produces 45 TWh of electricity every year (currently 38 TWh). Installed capacity increases from the current 15.3 GW to 20 GW.

- Along with photovoltaics, the "Energy Perspectives 2050+" also assumes a further expansion of the wind energy installed capacity (from the current 0.1 GW to 2.2 GW in 2050). The potential of electricity production from biomass (wood) remains rather limited (0.2 TWh).

An increase in electricity consumption due to electrification

- Final energy consumption per capita decreases by around 5%. At the same time, total electricity consumption increases from the current 58 TWh to 84 TWh. Electricity becomes the central source of energy for the heating (buildings) and mobility sectors. The mobility sector alone will consume around six times more electricity than in 2019.

  - The number of heat pumps – the more sustainable and efficient alternative to previous heating systems – will increase fivefold and become the most important heating system in buildings by 2050. Heat pumps are supplemented by local and district heating networks, in which a large number of heat sources can be used.

  - Mobility is a key driver of decarbonisation. Electric vehicles are efficient and cost-effective alternatives to conventional combustion engines and, by 2050, they will be ousted into technology museums. According to the recent study by EBP (EBP 2021), which is based on the “Energy Perspectives 2050+”, between 84 and 100% of driving will be carried out by electric vehicles in 2050. At the end of 2020, the electric mileage made up just 2%. The latest study by Swiss eMobility estimates the market share of electric cars will be 99% in 2035 (Swiss eMobility 2021).

In order to better interpret these targets, it is worth making a comparison using the “ice-hockey stick principle”. This describes the initially constant, then exponentially increasing growth figures for digital products and services until they reach a certain market saturation. The expansion of photovoltaics, as well as the increase in electric mileage as expected for the 2050 energy system, are easy to demonstrate using the “ice-hockey stick principle” (see Figure 2). Until 2019, the increase in installed PV capacity was steady and moderate. The previous developments for the electrification of mobility look more like the blade of an ice hockey stick than the long handle. If you then look at the characteristics of the 2050 energy system – with an installed capacity of 37.5 GW from photovoltaics and 100% electric mileage – the sales figures for photovoltaic systems and electric cars must increase exponentially in the coming years.

These developments necessitate further fundamental changes required to achieve the 2050 energy and climate goals. Alongside the switch to renewable and fluctuating electricity generation and the electrification of the mobility sector, there are other fundamental changes:

- Reliability of supply: bottom-up instead of top-down
- Ensuring electricity distribution: complex and expensive
- Market structure: Long tail instead of Pareto market

Reliability of supply: bottom-up instead of top-down

The energy system changes from a regime of controllable electricity production to a fluctuating regime. If around 40% of electricity production depends on the time of day and year and, above all, is independent of electricity consumption, the reliability of supply must be rethought.

It is self-evident that the massive expansion of photovoltaic systems in sunny months supports the reliability of supply. With every new photovoltaic system, individual electricity consumption can be covered during the day, making this a literal "fair-weather solution". In the winter months, when a particularly large amount of electricity is consumed, solar systems only produce

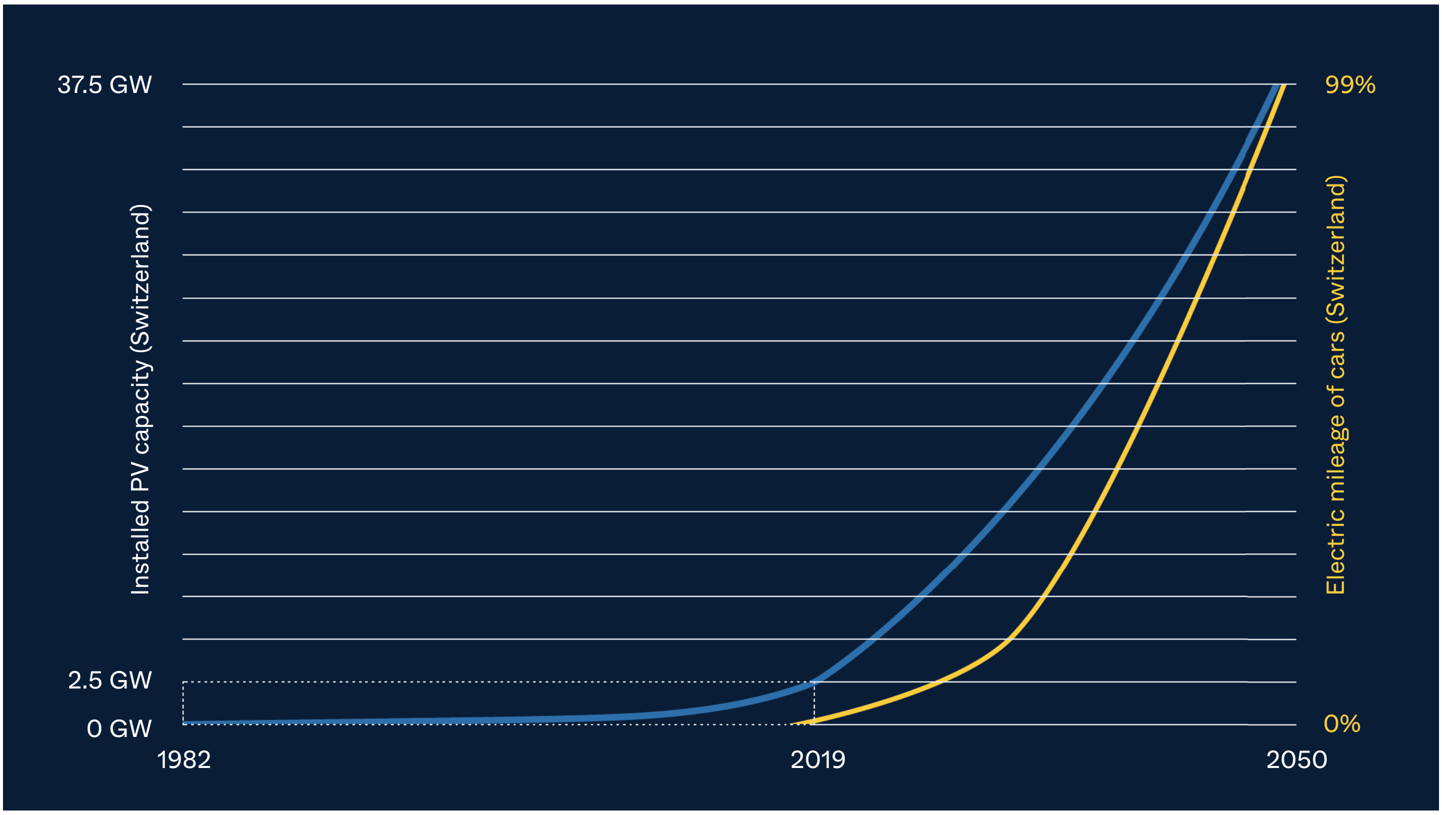

Figure 2: Trend of PV development and electric mileage by 2050. In accordance with (BFE 2020)

32% of their annual electricity generation. This means that the degree of reliability of supply reaches a plateau even in the event of a huge increase in electricity generation from photovoltaic systems. Battery storage technologies can increase the reliability of supply in the short term, but are not an economic alternative to the conventional connection to the distribution system and thus to other producers for longer low-sunshine periods. The reliability of supply of the energy system was simulated in HIVE for various municipalities using local energy self-sufficiency.

Scenario 1
To what extent does local energy self-sufficiency increase through PV expansion?

An increase in local electricity production from photovoltaic systems does not lead to an equal increase in local energy self-sufficiency in all cases. The duration of energy self-sufficiency corresponds to the total number of time intervals in which local electricity production covers local electricity consumption. However, “total energy self-sufficiency”, i.e. the ratio of total production to total consumption, is often used incorrectly.

The municipalities are currently utilising 2.4 to 6.2% of solar potential. Four of the five municipalities simulated by HIVE are currently unable to ever support themselves for 15 minutes with the installed solar energy.

- If 30% of the remaining solar potential is utilised, the municipalities are truly self-sufficient for 11 to 29% of the year. The total self-sufficiency is 20 to 72%.
- If 50% of the remaining solar potential is utilised, 19 to 33% true self-sufficiency is achieved. The total self-sufficiency is 30 to 110%.
- If 100% of the solar potential is utilised, the degree of self-sufficiency plateaus at 26 to 38%. The total self-sufficiency is 56 to 200%.

Scenario 1.1
To what extent does local energy self-sufficiency increase through PV expansion including battery storage?

Assuming that 100% of the solar potential is utilised, the addition of private battery storage with own consumption optimisation, which corresponds to 0.1% of the local annual electricity consumption, leads to an increase in the true degree of energy self-sufficiency from 26 to 38% to 36 to 54%.

Despite the expansion of renewable energies and additional generation from hydropower plants, Switzerland will still be dependent on electricity imports in 2050 and will have an import balance of 9 TWh in the winter months (SFOE 2020). However, the electricity import guarantee must be scrutinised:

- According to “Energy Perspectives 2050+”, electricity imports in winter consist primarily of wind energy generation from other European countries. Germany in particular, which will almost double its electricity consumption by 2050 due to the decarbonisation of the heating and transport sectors and will have high consumption levels in winter, will have to exhaust its own limited winter resources (BMWi 2021).
- The failure of the framework agreement with the EU, which reduces Switzerland's ability to import, increases uncertainty, thereby reducing the reliability of supply.

If there is a lack of large and controllable power plants and institutional uncertainties regarding Switzerland’s ability to import make further solutions difficult, reliability of supply must be rethought. A consistent and economically sensible coordination between electricity consumption and production, in order to ensure reliability of supply as locally as possible, is a first fundamental change to the 2050 energy system compared to the current situation. For the sake of reliability of supply, resources must be efficiently planned and used at an individual, local and regional level.

Ensuring electricity distribution: complex and expensive

The conventional electricity grid views itself as an infrastructure that ensures the transport and distribution of electricity from the place of generation to the place of consumption. Most electrical power is currently produced at a few central locations and transported to decentralised consumers. The benefit of this system architecture lies in the fact that the grid infrastructure has a clear division of roles. The transmission system operator must transport the produced electricity to the distribution system operator with as little loss as possible. This distributes the electricity to the electricity consumers via a weakly meshed distribution system: aorta and capillaries. With the electrification of economy and society in the 20th century, the distribution system was dimensioned and expanded in planable stages, according to the principle of the largest possible expected peak load. This principle has been able to ensure adequate performance – until now. The application of the same principle will reach its limits in 2050:

- The distribution system must create the necessary grid capacities to meet consumers’ increased electricity consumption, which also arises from the charging of electric cars. The distribution system must be dimensioned for the maximum supply capacity to ensure the customer does not experience any output losses. The maximum required supply capacity is based on the case with the highest possible power requirement from the grid and is also understood as a “heavy load scenario”. The highest possible power requirement occurs in a “residential district” grid area, for example, on weekday evenings in winter, when its own photovoltaic system does not produce any electricity, but in addition to high basic consumption, several electric cars are being charged in the district at the same time.
- The distribution system must also establish the necessary grid capacities to absorb and distribute the electricity production which is now being generated everywhere in the low-voltage range by photovoltaic systems. The maximum principle also applies here. The maximum required feed-in capacity is based on the case with the highest possible feed-in requirement into the grid and is also referred to as the “low load scenario”. The highest possible feed-in requirement into the grid is typically during the summer holidays, when the photovoltaic system produces a lot of electricity without much consumption. The distribution system must also be able to feed fluctuating electricity production into the distribution system.

The 2050 distribution system bears a “double” responsibility. It no longer supplies electricity to only one connection (vertical distribution of electricity), but must also be able to absorb excess electricity from the same connection and distribute it to others (horizontal distribution). In 2050, the distribution system is therefore also a peer-to-peer grid.

In HIVE, both the influence of increased power requirements due to electromobility and the increased feed-in requirements of the photovoltaic systems on the rise in supply and feed-in capacities can be locally modelled at a virtual connection point. It is also possible to calculate the effect of battery storage and PV feed-in management on the same.

Scenario 2
How does the electrification of mobility affect the maximum expected supply capacity from the grid?

If one assumes 100% electric mileage throughout Switzerland, the maximum expected supply capacity from the grid increases locally by up to 115%, based on the current situation.

Scenario 2.1
Can storage batteries reduce the new supply peaks in the grid?

No. Even a significant expansion of private, decentralised battery storage units (0.1% storage capacity of the local annual electricity consumption) with a focus on own consumption optimisation does not prevent the increase in supply capacities, as the storage batteries already have no stored capacities before the maximum supply peaks (“weekday evenings in winter”), due to low PV production and increased consumption.

Scenario 3
How does the PV expansion affect the maximum feed-in capacity expected from the grid?

If 100% of the solar potential is utilised, the required feed-in capacity must be increased by +1,000% to +3,200%.

Scenario 3.1
Can storage batteries reduce the new feed-in peaks into the grid?

No. The expansion of battery storage units (0.1% of the local annual electricity consumption) with a focus on own consumption optimisation does not prevent the increase in feed-in capacities, as the storage batteries already have no free charging capacities before the maximum feed-in peaks (“midday in summer”). To reduce the feed-in peaks, the storage units would have to start their battery charging cycles at around noon in the summer.

Scenario 3.2
Can PV feed-in management reduce the new feed-in peaks into the grid?

Yes. Feed-in management leads to lower feed-in peaks. Scenario 3 (100% utilisation of solar potential) forms the starting point.

- By reducing the maximum output of the respective photovoltaic systems to 70%, the increase in the necessary feed-in capacity of the distribution system is reduced to just +879% to +2,615%. The annual local PV generation is reduced by 0.1 to 2%.
- For 50% of the output, this corresponds to +595% to +1,832% feed-in capacity, 8 to 9% drop in generation.
- For 30% of the output, this corresponds to +300% to +1,033% feed-in capacity, 28 to 31% drop in generation.

Scenario 4
Does the electrification of mobility reduce the maximum expected feed-in capacities into the grid?

Yes, but only very slightly. Based on the full electrification of mobility (scenario 2), while simultaneously fully exploiting solar potential (scenario 3), the maximum expected feed-in peak is reduced by just 0.7% to 7%. The reduction of the feed-in peak depends on the extent of the charging capacity of electric cars at midday in the summer. At this time, electric cars are typically not charged at home, but rather at work.

The distribution system operator must guarantee the supply of electricity throughout the year. It must therefore dimension its grid capacities for the expected winter and summer peaks. A rise in the expected increase of the distribution system grid capacity traditionally leads to grid expansion. The cross-section of electrical cables is usually enlarged so that the maximum power required can be fed in or drawn from the grid. A high-profile study by BKW in cooperation with the University of Geneva assumes grid expansion costs of 11 billion Swiss francs by 2050. Since the 11 billion is financed by the customer, this amount represents very high opportunity costs.

Study by BKW Power Grid and the University of Geneva

In a GIS-based study, experts from BKW Power Grid collaborated with the University of Geneva to model the effects of the use of photovoltaics, heat pumps and electromobility on a distribution system that supplies 170,000 households in Switzerland and analyse scenarios for their pervasion over the years 2035 and 2050. Using a detailed grid model, the team of authors found that photovoltaics cause 18.5% and 13.7% more voltage limit values exceedances, respectively, compared to heat pumps and electromobility, which in turn cause slightly more line overloads, namely 0.5% and 2.5%, respectively. The team of authors also notes that the costs for grid strengthening depend significantly on the type of urban environment, ranging from 51 to 213 CHF/kWp, 46 to 1,385 CHF/kW and 34 to 143 CHF/kW for photovoltaics, heat pumps and electromobility, whereby the higher limit applies to rural areas. The total costs for strengthening the distribution system could be up to 11 billion Swiss francs by 2050, equivalent to CHF 2,900 per household in Switzerland. Interestingly, it has been determined that even at current costs, batteries have the potential to defer grid strengthening for up to 15% of transformer stations with the highest specific grid strengthening costs (Gupta, et al. 2021).

These 11 billion are to be understood as a best-case calculation. Within the best-case calculation, it is assumed that grid planners already know exactly when, where and how much additional supply or feed-in capacity is required, which means that the grid capacities of the affected grid areas would only have to be expanded once for 2050. However, the dimensioning of necessary grid capacities with conventional grid planning methods is reaching its limits with the increasing complexity of the situation: investments in the capital-intensive distribution system are generally conceived for the next 40 years. Grid planners make predictions for about 20 years in the future and dimension the distribution system for this period. In the past, considering a few (macro) variables was sufficient to estimate the predicted output increase. The prognosis models were able to predict the local and temporal output increase extremely realistically, as this only depended on a few factors. However, new variables that assign greater weight to complex interactions or individual behaviour must now be taken into account to plan a realistic distribution system for 2050. By taking such interactions into account, a grid planner can estimate when, where and how much additional supply or feed-in capacity is required.

The distribution system capacities must be adjusted for the increased electricity consumption and for the decentralised production in the distribution system. The best-case costs for ensuring the electricity supply through grid expansion at the distribution system level amount to 11 billion Swiss francs across Switzerland by 2050 (Gupta, et al. 2021). At the same time, the complexity of planning a productive and efficient distribution system is greatly increasing.

Market structure: Long tail instead of Pareto market

Until now, the traditional customer has played a passive role in the energy system. In a slightly exaggerated nutshell, their role involved paying electricity bills on time. The role of the conventional customer will change radically by 2050. The customer is a prosumer and can exert an unprecedented influence on many facets of electricity supply and energy trading with their own assets for electricity production, conversion and storage.

The prosumer can continue using their own assets to tackle their own energy targets with individual energy strategies such as own consumption optimisation, self-reliance, sufficiency, generating additional income, CO_2-neutral households, etc. In combination with the millions of assets of other prosumers such as neighbours or other asset owners, their true participation opportunities unfold. This is because the pooling of many small assets enables the prosumer to participate in system, grid and market services. The pooling of these assets leads to a new market structure.

In many sectors, only a few lucrative products that dominate the market are able to establish themselves on the market. According to the Pareto distribution: “80% of the turnover is generated by 20% of the products”. In contrast, in the long-tail market, there is a huge number of other products in addition to the top sellers that shape the market structure, despite the individual product having weak sales relative to the total sales of the market. The Pareto principle no longer applies: “In the long-tail market, 50% of the turnover is generated by 80% of the products”. Such democratic or egalitarian market structures are usually only possible if the search costs for the customer are kept as low as possible. In other words, there are only a few platform providers for such markets, e.g. Amazon, Apple, Spotify or Google.

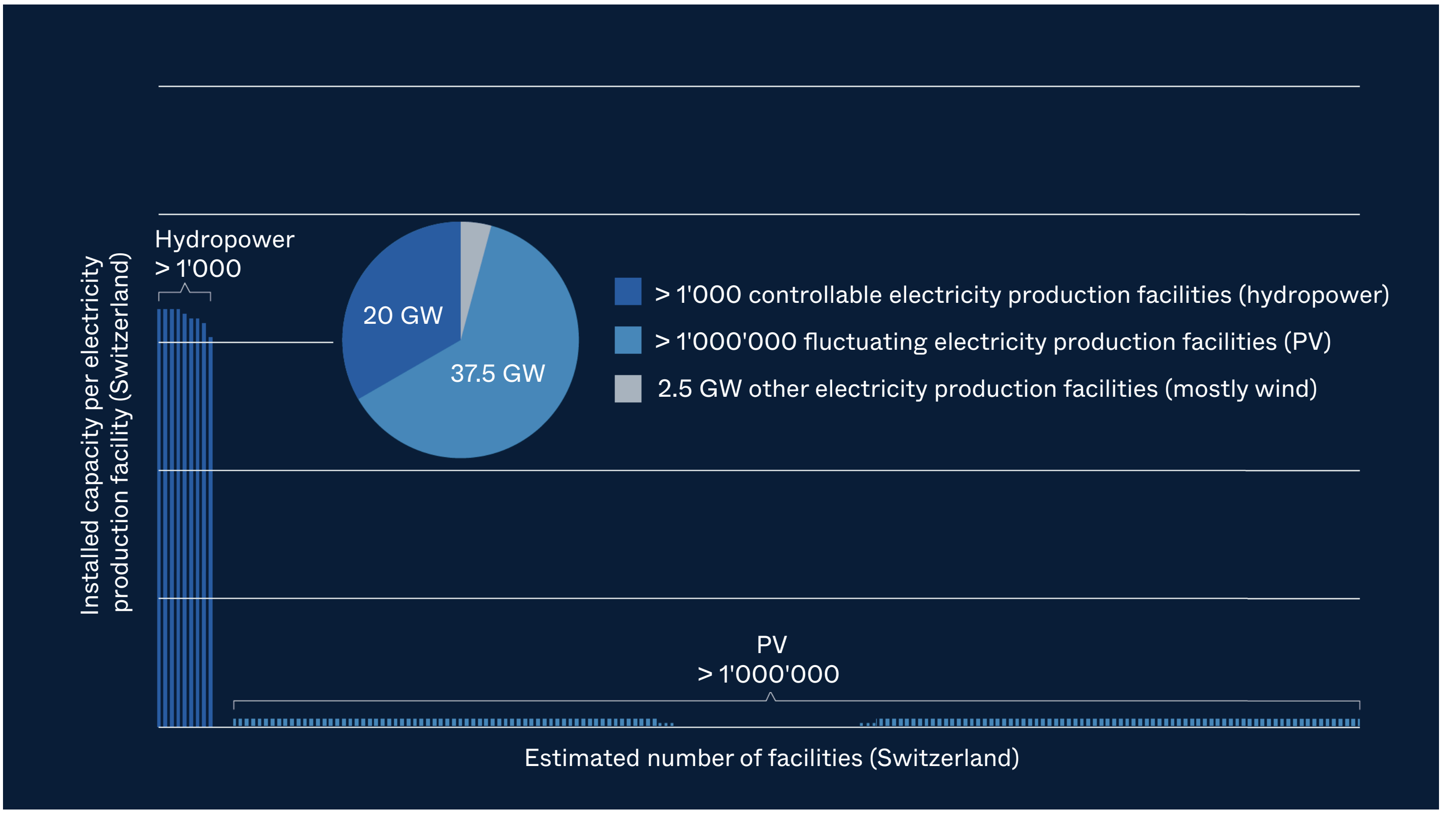

Figure 3: Example of a long-tail energy market structure for electricity production. In accordance with (BFE 2020)

Combined with hydropower generation, the millions of distributed production systems of the prosumers in 2050 represent a long-tail energy market (see Figure 3). The individual assets of the prosumer are irrelevant for such services due to the smaller size or capacity as a service provider. Combined, however, the PV assets produce around 40% of domestic electricity generation, as an example (SFOE 2020). As a result, a significant part of value creation shifts from central assets (such as hydropower) to decentralised assets. The Pareto market structure is replaced by the long-tail market structure. The 2050 energy system has democratic and participatory structures, leading to a new understanding of the role and responsibilities of the end user: in 2050, the energy customer is an active market participant. As such, the end consumer will not only benefit from a democratic and participatory energy system and actively help to shape it, but can also be actively guided – implicitly by necessary incentives and/or explicitly by new regulations. The prosumers are partially responsible for the efficient, safe and environmentally friendly supply of electricity.

For prosumers to be able to provide services in the long-tail market, a market design and a regulatory framework are required which allow them to do so. On the other hand, this necessitates a high degree of automation and technologisation of assets. Automation in the 2050 energy system affects all stages of value creation: energy supply, energy transmission and distribution, trading and sales. The automated control of different assets makes it possible to demand the necessary flexibility options. These serve not only to ensure increased reliability of supply at the local level or to protect grid capacities, but also to transform energy customers into active market participants.

Almost all of the prosumer's assets (and also the relevant assets of the distribution system or the electricity producers) are able to generate the necessary data and information that allow the prosumer to become an active market participant. The amount of exchanged data will increase. The rollout of smart meters alone will increase the amount of data by a factor of 40,000 (Keller and Freunek 2020). The interconnectivity of the assets increases this figure many times over. In addition to the data volume, data acquisition, transmission, processing and security must also be guaranteed to enable an automated control of assets (VDE 2019).

The 2050 energy system, which is characterised, among other things, by bidirectional electricity flows and decentralised electricity production, also generates bidirectional data flows through millions of asset data sets. While the "energy and grid" part of the system lies within the core competencies of current providers, the "technology and automation" part of the system offers new opportunities for providers who are actually industry newcomers. Technology providers boast a great skill set not only with regard to the data and information tasks mentioned above, but also when it comes to the development and commercialisation of digital processes, models, technologies, products, services and platforms. Due to the high levels of competitive pressure in their native markets, technology providers also have a high degree of business model innovation, development and scaling speed, and customer focus.

As has already been the case in other markets, the technology providers in the 2050 energy system will snag relevant market positions close to the customer to be able to bind customers as well as conventional energy providers with their own services using scalable business models. Another part of the value creation is thereby shifting from conventional energy suppliers, in which cantons and municipalities are involved, to international technology companies. Such business model innovations by technology providers are already proving themselves, particularly in deregulated energy markets.

The energy system will experience a profound change in value creation structures by 2050. On the one hand, value creation becomes "more democratic" through the prosumer's active market participation. On the other hand, it can be assumed that the technologisation of the system in turn favours an oligarchic structure, whereby technology providers with disruptive business models can take control of key market shares.

Energy cells: the new energy reality

The energy targets go hand in hand with **more difficult reliability of supply, increasing** complexity, a greater need for expansion of the distribution systems and new market structures. These cannot be guaranteed, mastered, financed or made possible with our current understanding. The energy system must therefore be strictly rethought. In order to meet the energy targets effectively and efficiently, a solution is presented which:

- decentrally solves decentralised challenges
- reduces complexity
- empowers prosumers to participate

So far, the solution concept has primarily attracted attention in Germany and Austria (VDE 2015, 2019). A cellular energy system and the term "energy cell" are only known to few industry decision-makers in Switzerland. The cellular energy system and the energy cells as well as their advantages are presented below.

Terms

In the cellular energy system, according to VDE (2019), the physical balance between energy supply and demand is established to the greatest possible extent at regional or even local level according to the subsidiarity principle. This balance is created by energy cells. An energy cell consists of the infrastructure for various forms of energy (electricity, heat/gas, mobility), in which energy cell management (in possible coordination with neighbouring cells) organises the balancing of generation and consumption across all existing forms of energy. The definition is supplemented by further explanations:

1. Infrastructure includes all resources used to convert, transport and distribute energy, as well as to store it.
2. The forms of energy considered include electricity, gas, heat and mobility. A cell can contain only one form of energy.
3. Energy cell management comprises all control technology facilities, including the required communication technology.
4. Neighbouring cells can be arranged hierarchically. There are thus cells at the same level as well as on higher and lower levels.
5. When balancing, which can be carried out seasonally or dynamically, three states can arise across all existing forms of energy: balanced, oversupplied or undersupplied.

The structure

The cellular energy system is a repeating and self-similar structure in the form of energy cells at various levels. The cell structure can largely be derived from the physical structure of the grids: from an individual household, a district, an (industrial) area, a village, a city, a region or even a country. A key aspect of a cell is its ability to independently organise the energy supply within the cell. A multi-level management system, including a behavioural order, is also proposed for the participants and tasks. The electricity and data flows can thus be coordinated and regulated at multiple levels, i.e. locally, regionally, interregionally, nationally and internationally.

The subsidiarity principle

The multi-level management system is based on the subsidiarity principle. This defines that any regulation deviations or problems that occur are primarily handled directly at the source of the problem and a remedy with the aid of the neighbouring upstream or downstream grid areas is only a secondary measure. Voltage limit exceedances that occur locally are thus first rectified by controlling local loads and/or storage options. Only once the local possibilities for self-stabilisation have been exhausted will upstream or neighbouring cells be brought in to solve the issue. The subsidiarity principle also applies to the organisation of data and information. Data is no longer evaluated, collected and protected centrally by a grid control point, but rather at the level at which information and knowledge processing seems the most sensible. Based on the subsidiarity principle, the following behavioural order arises for the individual agents in the cellular energy system:

1. The energy flow should be balanced within the cell / cell cluster.

2. The cell / cell cluster must, where possible, support neighbouring or higher-level cells.

3. The cell / cell cluster protects itself when neighbouring or higher-level cells are unable to provide sufficient support.

This behavioural order results in an overall behaviour structure or a swarm behaviour among all agents. These three swarm rules enable the transformation of a complex central system into a self-stabilising cellular energy system (Bayer 2021).

The energy cell manager

Cell management makes up the heart of the cell. The role of cell manager exists within each cell. Cell managers have control over a limited, locally linked infrastructure that can include generators, consumers, storage and energy converters. Cell managers thus exercise the rights and obligations of self-organisation in accordance with the subsidiarity principle. Cell managers which in turn contain and manage other cells, are known as cell cluster managers. The cell or cell cluster managers are responsible for their respective grid nodes. A grid node can be, for example, the house connection of a residential house cell, the transformer substation of a low-voltage cell cluster, the substation of a medium-voltage cell cluster, and so on. For example, transmission system operators, distribution system operators, industrial companies, district and area grid operators could thus take on the role of cell manager, or they can also be located in individual commercial properties or in households through the use of services for grid operation.

A cell manager can offer the flexibility options available to it for applications which support the system, grid, and market. The flexibilities can be prioritised for one application over the other, depending on need. Grid-supporting applications can be prioritised over market-supporting applications if local control measures are necessary to stabilise the electricity grid. The cell manager automatically regulates all energy flows within the cell and also coordinates the energy supply and demand with upstream or neighbouring cells.

Digitisation and automation

The role of cell manager requires a minimum level of monitoring and control options. In the simplest case, this device collects all the necessary information for each cell and is equipped with algorithms that enable the cell to operate in a way that is as optimised for self-consumption as possible across different scenarios. In the second step, communication among upstream and neighbouring cells can also be mapped, with higher-level algorithms making further balance processes possible. Cell and cell cluster managers then have accurate information about the grid status and the flexibility potential of the cell cluster. A complete digitisation of the cell is illusory and not necessary. However, in order to make an accurate prediction, a minimum level of monitoring is required.

Why is a cellular energy system needed?

Energy cells take into account local conditions, potentials and disruptions and, in accordance with the subsidiarity principle, offer more effective solutions than would be possible under a “one rule fits all” format. The cellular energy system should enable decentralised solution approaches for local challenges that arise from decentralised production and feed-in. At the same time, it can be more accurately determined to what extent a cell can support another cell in the event of need.

Both the number of participants and the proportion of volatile electricity production increase the complexity of the system as a whole. The complexity of the system as a whole is reduced by enabling decentrally distributed cell managers to self-organise their “own” infrastructure. A cell manager monitors and coordinates a manageable number of linked infrastructures.

System-wide failures can be reduced by locally isolating faults. In the event of deviations from normal operation, energy cells could disconnect from the grid, switch to isolated operation and, if necessary, also start resynchronisation. The first pilot projects for the isolation and resynchronisation capability of energy cells are currently being carried out in Germany. The identification and rectification of faults requires rapid responses. If faults are detected and rectified too slowly, damage and/or further faults could occur. The local rectification of a fault by the cell manager provides a fast-response alternative to conventional central control, for example via a grid control centre. The distribution of the control responsibility and decentralised data management also reduces the impact of cyber attacks on the system as a whole. At the same time, information security in the cellular energy system is becoming increasingly important as the communication structures grow with the rising number of capable cell managers.

The local or, in the case of larger systems, regional organisation of the energy supply and storage as well as the local or regional balancing of the energy demand can reduce the grid expansion of the distribution system through the use of grid-supporting flexibility offers from the cell(s) (BDEW 2016). With the increased level of control at the low-voltage level, necessary maintenance activities can also be carried out at the medium and low-voltage levels.

Ultimately, local management can increase the sense of responsibility and intention to contribute in households with regard to climate and energy targets (Hertig 2019). This can even result in “altruistic competition” within and between the cells.

Energy cells: The practical approach

Endaprime's practical approach supports consumers in their pursuit of local energy self-sufficiency and aims to implement the first behavioural rule of the cellular energy system. An energy cell consists of any consumers in a district, village or region who strive for smart energy self-sufficiency in a scheduled manner with regard to energy generation, for example with photovoltaics, hydropower, wind turbines or biomass. To this end, Endaprime algorithms regulate consumption and generation, taking into account other relevant aspects (such as grid and storage capacities). Using the current approach, the electricity supply compensates for generation bottlenecks in the energy cell through additional hydropower, neighbouring cells or other conventional energy sources via the distribution system. Storage solutions to bridge the bottlenecks are currently being researched and are in trial phases.

Endaprime believes that the 2050 climate and energy targets will be met using this approach. The planning and operation of a cellular energy system are becoming complex, interdisciplinary tasks that require support through artificial intelligence and analytics. BKW's technology and innovation hub – Endaprime – is already developing solutions for this new reality.

For further information about Endaprime or HIVE, please visit our website.

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Abbreviations

TWh	terawatt hour
GWh	gigawatt hour
PV	photovoltaics
kWp	kilowatt peak
kW	kilowatt

To improve legibility, gender-neutral terms have been used throughout the text. All personal designations apply equally to all genders.

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