The Energy Cell System

A future-oriented concept for a resilient energy supply system

Our current energy system is facing major challenges and changes. The switch from fossil fuels to renewable energy sources is not only changing the way we generate electricity but also requires a fundamental rethink of the structure of our energy supply system. The energy cell system offers a promising approach that can reconcile security of supply, sustainability and local responsibility. It is a concept that makes complexity manageable through decentralized functional units and ensures stability through distributed, autonomous but interacting units. By establishing a networked system with clear rules for cooperation, the energy transition can be achieved more efficiently and effectively while at the same time increasing the robustness of the overall system. Cooperation between the individual cells and clusters also makes it possible to bundle behaviours that benefit the system without further increasing complexity.

From centralized power plants to a decentralized energy landscape

Our previous energy system was based on a few large power plants. Energy was generated centrally, but often as close as possible to the centres of consumption. This system has reliably supplied us with electricity for decades. However, with the switch from a few highly available large power plants (with synchronous generators) and the associated energy transition to millions of small plants that can only generate electricity depending on the weather, this system is reaching its technical and physical limits. In addition, more and more players need to be integrated, be they generation plants, storage facilities, market players or flexibilities. This is not possible without comprehensive networking and digitalization, which also significantly increases complexity and brings with it completely new challenges. For example, previously unknown side effects of complex systems that cannot be controlled with our previously successful linear thinking or the risk of cascade effects must be expected.

Current misguided developments

Paradoxically, however, current developments are going in the opposite direction: we are experiencing an expansion of international electricity trading and an considerable increase in complexity and interdependencies - exactly the starting point for potential disasters. In future, almost every country would like to export when there is a surplus of electricity and import when generation is too low. In future, almost every country would like to export when there is a surplus of electricity and import when generation is too low, but the grid infrastructure was never designed for this.

In addition, the expansion of international electricity trading increases the risk of cascading outages. This is because a high level of exchange with neighbouring countries means that too little is produced at home. If a disruption occurs, it can also spread more easily over a large area, as we saw on January 8, 2021 with the grid disconnection in the Balkans. Even though this event ended mildly, it was just a foretaste of other major disruptions to come. It is also paradoxical that Germany in particular is increasingly trying to compensate for planning and implementation errors through micromanagement, such as with the current Solar Peak Act. Many of those responsible do not seem to realize that such regulations cannot be implemented overnight or are even contradictory. Nor do they realize that this will trigger a series of side effects with delayed effects. It seems to be a case of out of sight, out of mind. Not to mention the fact that no one can really keep track of the associated complexity, let alone master it.

The basic problem is almost always the lack of program planning with corresponding controlling and adaptation to changing framework conditions. It must be emphasized here that this is not about micro-management, but about "orchestrating" the framework conditions. For example, power plants may only be demolished when an equivalent replacement is available. Above all, it is about a coordinated approach. While there are very clear and strict guidelines for expansion on the generation side, particularly for weather-dependent electricity generation from wind power and photovoltaics, there is only a patchwork approach to storage and grid expansion and conversion, with costs increasingly spiralling out of control.

This is an extremely questionable approach in a system in which consumption and generation have to be constantly balanced with very little flexibility and where physics does not forgive serious mistakes. There is simply too much confidence here that the existing large-scale system can continue to successfully compensate for these errors, without taking into account the fact that large-scale power plants are constantly being reduced or temporarily switched off when PV and wind power feed-ins are high. In system theory, however, stable, complex systems are masters at buffering faults. However, if there is no time for regeneration, there is a risk of serious damage and even system collapse.

We also know from systems theory that the stability of a system increases with networking. But not endlessly. To maintain robustness, substructures are needed above a certain size, otherwise the overall system becomes unstable and collapses. In other words, exactly the opposite of what is currently happening with the expansion of the electricity market without taking into account the systemic and physical framework conditions.

The energy cell system - a concept inspired by nature

In order to create a stable and robust system, the energy cell system is based on nature: just like cells in organisms, small, autonomous units should work together in the energy system to achieve a larger whole. Each "energy cell" initially supplies itself and exchanges energy with neighbouring cells ("breathes") as required. The whole thing must of course be "orchestrated" at a higher level, but without the centralized control approaches that are being pursued today. The main aim is to harmonize local action with the overarching requirements in order to achieve optimum system stability and efficiency. As always in a systemic environment, it is a question of as well as!

You can think of it like a large orchestra. Each energy cell is an instrument that plays its own piece, but at the same time synchronizes with the others to create a harmonious whole. Networking takes place by connecting all energy cells with each other, but at the same time a minimal and clearly defined data exchange takes place, which also minimizes cyber risks. A common "energy sound" serves as a source of information, while each cell acts locally and autonomously. The intelligence is located at the respective network nodes. Not to mention the fact that no one can really keep track of the associated complexity, let alone master it.

A plausibility check at the respective grid nodes using simple physical measurements is also central, making it easier to detect errors or manipulations (e.g. hacker attacks) and prevent possible negative effects.

These decentralized structures follow the principle of subsidiarity, according to which problems should be solved where they arise. The self-organization of such systems leads to more order and reduces the possible tendency towards disorder (entropy). Similar to the Internet, which was developed according to the principle of decentralization, the aim is not to replace all existing structures, but to supplement them with a bottom-up approach and make them more robust.

The current central control structure was introduced with EU market liberalization ("unbundling"). Prior to this, the energy supply companies were de facto cluster managers who controlled generation, consumption and grids in their area of responsibility. In this respect, energy cells are nothing entirely new, but the framework conditions have changed significantly in the meantime. In any case, a small-scale, decentralized grid and supply structure cannot be effectively controlled with central management and an inadequate level of digitalization.

In the cellular approach, the control structure is integrated into the decentralized grid structure. Starting from the smallest units, the cell managers at the house connection, via a cluster manager in the transformer station to the higher-level cluster manager in the substation, a decentralized control architecture is created that is congruent with the physical grid structure. At this scale, it is also possible to react appropriately to meteorological conditions and take the necessary compensatory measures. However, initial approaches will tend to be smaller, as already realized industrial networks (cells) show. In other regions, such as the USA, energy cells are also known as microgrids and are currently being implemented.

Swarm intelligence as a basic principle

The functioning of the energy cell system is based on rules borrowed from swarm intelligence. Similar to birds in a flock, which can form complex formations without central control, energy cells also function according to simple rules, which together result in a stable system:

1. Try to balance the energy flow within your cell/cluster of cells.
2. If possible, support neighbouring and higher-level cells/cell clusters.
3. If the support of neighbouring cells/cell clusters is not sufficient, protect yourself.

With these rules, the increasing complexity of the central system can be transformed into a decentralized, self-stabilizing cellular system with a high level of resilience. The interacting participants act according to simple rules and thus create order in the chaos without central control.

The particular charm of this approach lies in the fact that it can be implemented bottom-up during ongoing operations without endangering the overall system. Different cell concepts can also be explored, as there is not just one solution. In this way, it would be possible to quickly replace the current chaotic approach with a structured approach.

Another pragmatic approach would be that anyone wishing to participate in the electricity market must be able to guarantee to supply electricity for a certain number of hours per year and within a fixed CO_2 budget. This would automatically lead to cooperation and many problems would solve themselves without micromanagement and increased costs.

Advantages of the energy cell system

The energy cell system offers numerous advantages over the conventional centralized approach:

1. **Increased stability and reliability**
   A key feature is the increased immunity to interference and the ability to correct faults more quickly, as their spread can be limited. In the event of a major disruption, the energy cells can disconnect from the higher-level grid and continue to operate autonomously with a predefined reduced output, e.g. to supply vital infrastructure. This significantly reduces the impact of potential power outages.

   In the process planned today, the local end devices (e.g. heat pumps, charging stations, battery storage units) are controlled from a few central data centres or control rooms. In the event of communication failure or errors, the switching states remain in the last determined actual state. A switched-on photovoltaic system therefore feeds into the grid regardless of possible demand. In addition, many distribution grids lack the digitalization required for effective control. Not to mention controllability in the event that the grid has to be reconstructed.

   A distinction is made between two failure modes in the cellular energy system. The failure can affect supra-regional communication or - in the worst case - lead to a total communication failure. If communication is possible at local level, data is exchanged as far as possible. The cluster manager, which detects the communication failure, continues to work with its locally measured network status parameters and adapts its behaviour to these measured parameters of the upstream network. Internally, the cluster manager continues to operate and control its subordinate cluster and cell managers and its grid and behaves externally in a grid-responsive manner. A total communication failure means that the cluster and cell managers cannot exchange any data or information. In this mode, the cluster and cell managers continue to work on the basis of the locally measured parameters and retain their protective functions. In addition to its potential suitability for local or regional island operation, this decentralized architecture also offers many advantages when redesigning the transmission and distribution grid. Thanks to the decentralized intelligence, large grid areas are not supplied with electrical energy all at once, which leads to considerable problems with grid stability, but the reconnection takes place on a small scale, in a controlled manner and without large load jumps.

2. **Better integration of renewable energy**
   Decentralized functional structures make it much easier to integrate renewable energies. Through local and cross-sector storage solutions (batteries, heat storage or electric cars) and cross-sector energy management, fluctuations in demand can be balanced out in the best possible way at a local level. This reduces the need for expensive and controversial grid expansion. The central element here is energy management, which has hardly featured in the public debate to date.

   Cellular operation also requires an "insurance system" that rewards those who work efficiently and in a way that serves the system. Major deviations, which can also affect neighbouring cells, must be subject to sanctions in order to create incentives for careful operational management. This is intended to prevent the current practice of acting at the expense of the general public.

   The current practice, whereby once grid connection capacity has been paid for, it entitles the user to purchase as much energy as possible at any time, is neither up-to-date nor conducive to the grid in a renewable energy system. Purely variable electricity prices do not adequately reflect the costs. Instead, in the event of energy surpluses, it should be possible to increase the supply capacity without higher connection costs. Conversely, the power provided and secured around the clock should be minimized through cost incentives. In this way, the actual provision costs for the grid infrastructure are allocated more appropriately and incentives for grid-friendly behaviour are created.

3. **Increased energy efficiency**
   Decentralized energy generation enables the use or better integration of waste heat, which is often released into the environment unused in central power plants. As energy generation takes place closer to consumers, losses during transport are also minimized, making decentralized systems more resource-efficient.

4. **Strengthening local economic cycles**
   Decentralized energy supply creates jobs in many regions and promotes local economic development. In any case, people are more willing to adapt to the needs of their energy cell than if it is "controlled from above". Local communities can also be involved in decision-making processes and benefit from the added value. This also addresses an important social function.

5. **Energy autonomy and price stability**
   Those who rely on decentralized energy generation and supply can at least partially decouple themselves from price fluctuations on the electricity market. This also increases planning security for companies. With the cellular approach, it is also possible to link local and regional grid bottlenecks or surpluses with market incentives and balance them out better. The current electricity market may ignore the physical realities and assume a "copper plate" as the basis for action, which leads to considerable redispatch costs, for example, which are burdened on the general public and not the originators. A fair electricity market must therefore take into account the physical possibilities and limits of the grid and ensure that costs are allocated according to the originator.

Challenges during implementation

Despite all the advantages, the energy cell system also presents some challenges:

1. **Initial investment vs. long-term costs**
   Of course, the construction of an energy cell initially costs money, as additional operating equipment, control facilities or an energy management system are required. As is usual with infrastructure projects, it takes a long time for the costs to be amortized. A longer-term assessment standard is therefore also necessary here. We need to start evaluating such investments according to their life cycle costs. The construction of a production hall with a poorly insulated building envelope and a high-temperature gas heating system is considerably cheaper in terms of investment than a well-insulated building with a low-temperature heat pump. However, over a service life of 50 years or more, the more efficient building saves many times the initial higher investment costs.

   Until the energy crisis, this was hardly feasible in terms of price. With the price increases since then and the foreseeable increase in volatility, this is changing. Above all, the chaotic and unsystematic implementation of the energy transition will foreseeably become more and more expensive. Not to mention the costs if something major were to go wrong, which from today's perspective is only a matter of time.

2. **Technological complexity**
   The integration of different energy sources and their control is quite complex. Practical experience has shown that the integration of different systems often poses major challenges. Better standardization is required here. Although there has been discussion of smart grids for over 15 years, little seems to have happened here so far. At the same time, there is hardly any way around it, as the centralized control practiced today is increasingly reaching its limits or has many costly side effects.

3. **Regulatory and legal obstacles**
   The implementation of decentralized structures is currently hindered by existing laws and regulations, as these are rigidly geared towards the central energy

supply system. A rethink in policy and regulation is urgently needed here in order to adapt the regulatory framework to the new technologies and concepts. Especially in times of great changes, we need more freedom and not more detailed regulation and micromanagement, as it is currently being practiced.

4. **Financing issues**
   The often constructed contradiction between solidarity in the network and the supposed egoism in the realization of an energy cell is based on the previous cost-intensive individual measures, inadequate implementation ("energy communities") or the current financing basis of the common network.

   These are also the negative side effects of market liberalization, which lead to a fragmentation of the supply system. Nobody really feels responsible for the overall system any more. On the other hand, there is a belief in centralized control. Even though the model of market liberalization has been very successful for two decades and has led to falling prices, the framework conditions have changed fundamentally in the meantime. More of the same therefore does not lead to something better, but rather to chaos. Only by thinking systemically and implementing the energy transition can we keep the increasing complexity under control, unless we override the laws of nature and the findings of evolution.

The path to a solidarity-based energy system

A cellular energy system is by no means lacking in solidarity, quite the opposite. It is based on mutual support and shared responsibility: end consumers, operators of decentralized generation, storage and conversion systems contribute jointly to decentralized security of supply. The principle of subsidiarity ensures that problems are solved where they arise. These reliefs the burden on higher-level structures and resources are used more efficiently and, above all, more effectively. The need for higher-level infrastructure and expensive compensatory measures is reduced.

An opportunity for a sustainable future

The energy cell system therefore offers the opportunity to shape the energy transition in a holistic and future-proof way. It requires great efforts, but also offers enormous opportunities for innovation and sustainability.

The energy transition is not just a technology transition, but above all a cultural transition. It is not a question of either/or, but of both/and. The large-scale technical system will certainly continue to provide us with important support for many decades to come and is indispensable in many areas. However, a decentralized bottom-up approach can increase the robustness of the overall system during operation.

Ultimately, our highly optimized large-scale system is more efficient than a cellular approach, but only until an event causes a major supra-regional disruption that cannot be rectified within a few hours. Security and redundancy cost money, but especially in the power supply sector, where there is such a high and critical dependency on supply for our society, this must not be a question of "nice to have", but a question of survival.

The massively changing generation landscape requires adapted, robust structures. The energy cell system offers a way to meet this challenge while combining resilience, sustainability and social participation. It is now up to all of us to play an active role in shaping this change. The energy cell system is not a distant utopia, but a practical and efficient solution to the challenges of our time.

The authors

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