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RESEARCH

Building the pyramid of grid analytics.

The path to data-driven network planning and operations.

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Executive summary.

The energy system is changing according to fundamental trends – the transition to renewable energy, the decentralization of generation, the electrification of loads, and of course digitalization. These trends are introducing new challenges to both transmission and distribution system operators. Although their challenges manifest themselves differently, they can be generally grouped into two categories:

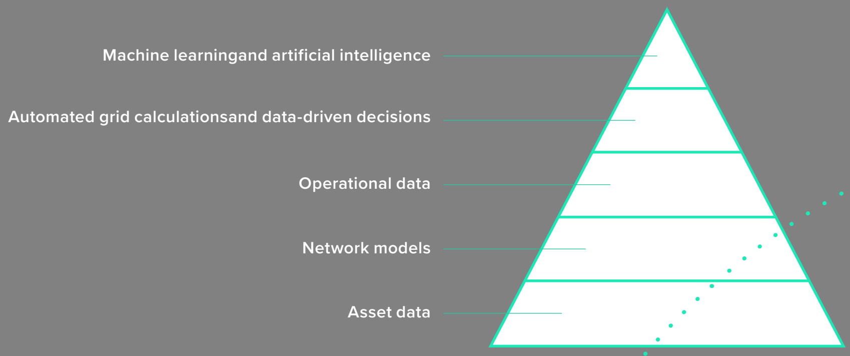
- The need to invest to increase the capacity of the grid, while maintaining existing assets and facing finite revenues and a finite workforce
- Rapidly growing uncertainty in both short-term and long-term power flows, caused by the increasing weather-dependence of power flows, the electrification of energy consumption, and the timeline misalignment of load growth and grid development.

Conventional approaches are not able to deal efficiently with these challenges and are becoming less effective and more labor-intensive. This is where grid analytics can help, by adopting data-driven approaches and processes across the organization.

Grid analytics can be described as a pyramid (shown below), which should be built up layer by layer from the base. Implementing processes that will ensure the quality of each layer is vital, otherwise value delivery suffers, leading to a loss of trust in such innovations and to resistance. Use cases that only require partial data are great for experimentation and building up capability and necessary processes.

Network operators have developed a culture, which is driven by the nature of the business, the stakeholders involved, and the legal framework they operate in. The approach to the implementation of grid analytics and innovation, has to be tailored to this culture. Namely, it should be evolutionary "planned innovation" focused on standards, guidelines, and processes, with particular attention to data quality and the user experience of these new processes.

Continuing efforts to foster both national and international collaboration is necessary, as well as a broader discussion on the legal framework and its pitfalls.



Inevitable trends.

There are fundamental trends that are transforming the whole energy business. With the exception of digitalization, which is taking the whole economy by storm, the main drivers of change in the energy business are the growth of renewables, the decentralization of generation, and the electrification of energy consumption. These trends and their predicted magnitude are the source of major challenges, particularly for distribution and transmission network operators.

Growth of renewables

Progressing climate change and worldwide efforts to decarbonize the economy are driving the growing investments in renewable energy. An increasing share of renewables in the energy mix inevitably leads to the rapid growth of installed generation capacity, due to the lower load factor of renewables compared to fossil fuel plants and nuclear plants. In the Netherlands, in order to meet the government's targets to cover 70% of the current electricity consumption through a combination of wind and solar power, the installed capacity has to increase by roughly four times. All this new installed capacity has to be accommodated by the networks.

Decentralization of generation

Historically speaking, generation has been predominantly covered by smaller numbers of large power plants connected to the transmission network. However, a significant part of the newly built renewable generation consists of smaller-sized projects connected to distribution networks. In periods of solar and wind booms this often leads to the congestion of HV/MV substations. Solar generation is also often built on the rooftops of houses and businesses and is connected to low-voltage networks or behind the meters. In the Netherlands, there was 4 GW of rooftop solar installations at the end of 2018, which is more than 20% of the maximum system load, and further growth is expected.

The decentralization of generation has a dramatic impact on power flows in the networks, often leading to reverse power flows and making them much more unpredictable. Additionally, small-scale installations do not typically offer the same control capabilities to contribute to voltage and frequency regulation as conventional synchronous generators do. And in cases where they do, the frameworks and mechanisms to effectively use and verify the provision of these ancillary services are often not in place. Coordinating the response of large numbers of small generators is also a more complex task than controlling a few large generators.

Electrification of energy consumption

The electrification of fossil-powered energy consumption, such as heat generation or transportation, is one of the keys to decarbonizing our economies. It will also inevitably lead to an increase in electricity consumption and a growth of load. Additionally, the concurrence of these new loads, and their dependence on weather and other external triggers is rather high.

For example, personal electric vehicles are mostly charged upon arrival at the office or home. Their energy consumption also increases in winter as the batteries and cabin need heating up, and winter tires are less efficient. Electric buses and trucks will charge mostly after traffic peaks as well. Heat pumps and electric heaters operate more in winter and around typical shower times; electric stoves are mostly used around typical cooking times; and industrial loads typically peak during working hours.

As grids have to withstand the peak load, an increase in load and a high concurrence of loads located close to each other pose an enormous challenge. Industrial loads and some aggregated household loads might be able to offer some flexibility services, which can be good mitigation measures in the most critical cases, but they are generally not enough to reverse the impacts of this trend.

Challenges network operators are facing.

Although the trends are impacting the whole energy industry, the categories of challenges that network operators are facing manifest themselves differently in transmission and in distribution.

In transmission, the number of assets is relatively small. The challenges come from the increasing technical complexity brought about by installing HV and EHV underground cables, introducing HVDC systems, and increasing the penetrations of power electronics-based generation, as well as from a number of operational aspects related to balance responsibility, voltage control, maintaining secure operation (n-1), and international interdependence.

In distribution, a big part of the challenge comes from the sheer number of assets. Furthermore, the need of active decision-making is growing due to the increasing variations of loads across the network and growing variety of available mitigation measures.

Need to invest

All the newly installed renewable generation and electrified loads will require significantly more capacity than our networks can withstand at the moment. Additionally, as the grid has been gradually developed over the last century, there are a lot of assets that were installed several decades ago and that are approaching their end of life. Therefore, there is a need to continue renewing the asset base and at the same time significantly expand the capacity of the networks.

Insufficient or unwise investment and maintenance are not an option. These would lead to a hampering of the energy transition and could cause a noticeable drop in grid reliability, which in turn would have a negative impact on both the economy and quality of life.

The income of network operators is regulated and to a large degree is determined by tariffs for transmission and distribution. A dramatic increase in tariffs would therefore inevitably face strong public and political resistance. At the same time, even if additional funding for the grid operators could somehow be secured to boost investments, there is only a limited number of technicians to actually carry out the work. A shortage of technical staff has been a prevalent problem in the industry for several years, and fast scaling up is not feasible, as education, skills, and experience are vital to carry out the work safely and with the desired quality.

Rapidly growing uncertainty

The growth of weather-dependent renewable generation (wind and solar) and weather-dependent loads (electric vehicles, heating) transforms the nature of previously predictable power flows in the networks. The speed, frequency, and severity of the changes in power flows are reaching previously unseen levels. Power flows can differ dramatically within one day, from one day to another, and also between seasons. At the same time, the power flows are far less predictable. This creates challenges both in planning and operations for both distribution and transmission. The designs of networks have to be more accommodating, maintenance has to be planned far more carefully, and the number of operational decisions needed to prevent congestion and voltage issues continues to increase.

The major source of long-term uncertainty lies within the fundamental trends – when, where, and how strongly will these trends manifest themselves? In other words, how will the number of heat pumps, electric vehicles, and solar panels grow in time and across locations?

This is further amplified by the mismatch of timelines for grid development on the one hand, and electricity consumption change and renewable projects development on the other. For example, it takes up to two years to develop and build a green-field PV project, but it typically takes a year or two longer to increase the capacity of an HV/MV substation, and in cases where the HV lines to this substation also need to be upgraded, it can take up to ten years. Reinforcements in EHV transmission can take even longer. At the same time, once a business case is identified, new technologies can be adopted quickly.

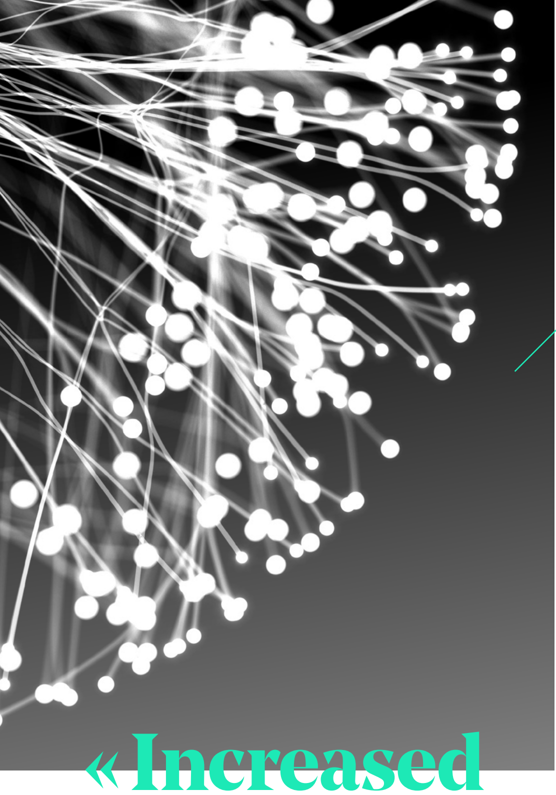
Conventional approaches will not suffice

Considering the need to invest, the pressures the network operators are facing from all sides, and the growth of uncertainty across the board, it is clear that network operators must act more intelligently and effectively than ever before. Conventional approaches are not ready for such an increase in uncertainty and the speed of change, and they would inevitably lead to excessive investments. And as indicated above, a rapid growth in investment is not feasible due to budget restrictions and a finite available workforce.

Traditionally, planning and operations are carried out on the basis of standardized procedures and designs, which are essential parts of processes throughout the network operators' organizations. Such standardization has ensured robust designs and safe operations, while significantly reducing the risk of human error and ensuring sufficiently quick decisions. However, some assumptions behind these standards and guidelines are no longer valid, making some of them obsolete and increasingly ineffective.

Examples of assumptions that are no longer valid

Load and concurrence	The designs of LV networks count with a certain load per household and concurrence of loads. This has been an effective approach, but the addition of electric vehicles, heat pumps, and solar panels causes loads to grow in multiples and makes them largely concurrent. The load in LV networks is becoming highly dependent on the penetration of these technologies, which differs geographically and over time. As a result, the assumptions behind standards and guidelines for LV network design are no longer valid.
Time for reaction	Networks are designed for peak loads, which have historically grown at a steady pace, and with a margin to accommodate for the expected growth. As a result, potential capacity issues were seen years ahead, giving enough time to plan adequate grid expansion. The fast adoption of renewables and the electrification of loads in a given area causes a rapid growth in load, which can lead to congestion and does not provide enough time for network operators to react.
Voltage control	In distribution networks, power used to flow in one direction – from transmission to consumers in LV networks. Appropriate voltage levels have been ensured by following simplified design guidelines that were universally applicable, and little effort in operations has been required. With increasing distributed generation and electrification of loads, large swings between production and load can be observed across distribution networks. The swings in power flow are causing previously unseen swings in voltage, making the design guidelines ineffective and requiring more effort to actively manage voltage in distribution grids.
Number of operational decisions	In the past, the power flow in the transmission network was to a reasonable degree predictable – with known load centers and generation locations, with predictable load and generation, following a slowly changing price-determined merit order. This meant that a reasonably low number of operational decisions was needed to operate the grid securely, and these decisions were often related to maintenance and failures. The growth of renewables makes power flows more unpredictable across tcountries. Furthermore, the electrification of loads and distributed generation make the "load" side in transmission increasingly unpredictable as well. This requires a lot more effort in operations, including predictions of power flows.



Path to grid analytics.

« Increased efficiency by data-driven processes has been a nice-to-have, but to deal with the challenges of energy transition, it is a matter of survival. »

The demands on the planning and operations of networks are continuously increasing, at what appears to be an exponential rate. At the same time, conventional methods and measures are becoming less and less effective. Additionally, technological advances in communication and control protocols, storage, etc., increase the variety of potential solutions. As higher asset utilization will be required in the future, more tailored solutions will be adopted and more active decisions will have to be made, both in planning and operations. It is vital that these decisions and related processes are data-driven to reduce the risk of human error and to ensure a high reliability of electricity supply. This is where grid analytics can support network operators. It is important to point out that grid analytics should not mean an abrupt adoption of the most novel artificial intelligence algorithms and technologies, but rather a thorough, methodical adoption of data-driven approaches and processes across the organization to ensure the efficient usage of assets and effective investments.

Pyramid of grid analytics

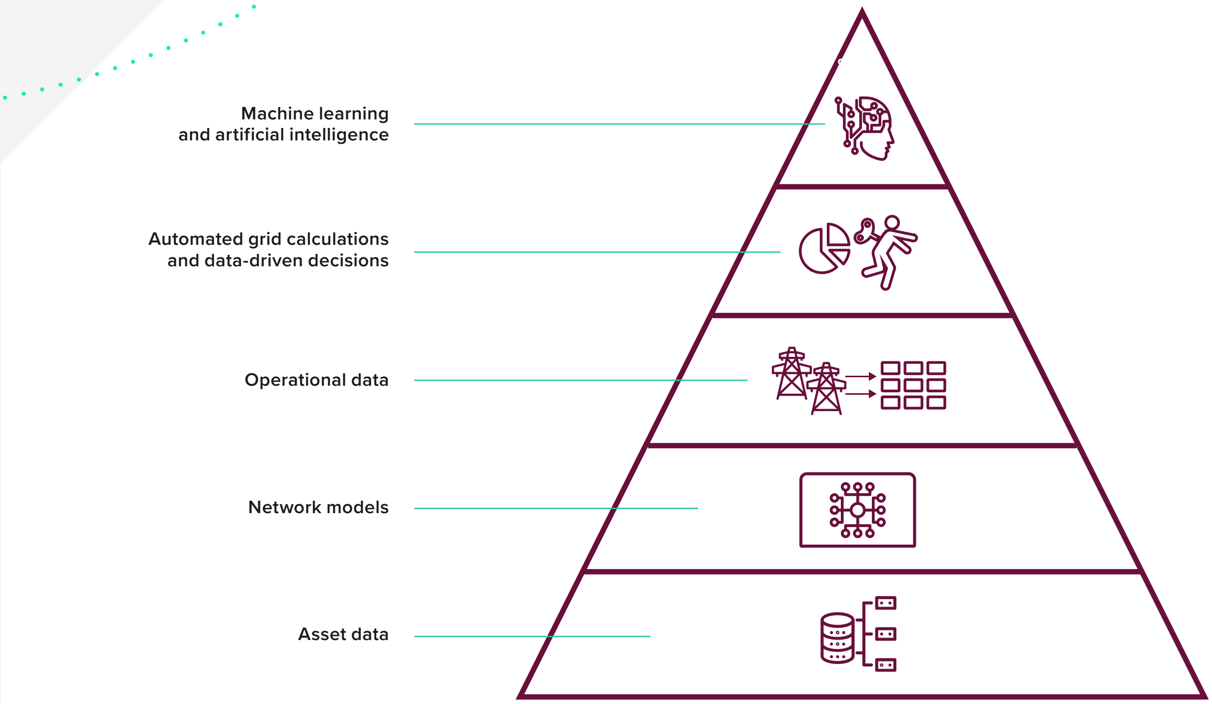
The pyramid of grid analytics consists of different layers. These layers describe the adopted data and approaches and gradually increase in complexity.

Asset data

Asset data stored in a database together with tools and methods to access and interact with this data form the base of the pyramid. This data should not only include the assets owned by the network operator but also basic data of relevant client assets. In transmission, this means, for example, data of connected generators or the typical load of substations. In distribution, it can include data about the presence of PV installation or typical consumption of customers. The data has to be clearly structured in a uniform format to allow effective usage by algorithms. The vast majority of European network operators have such databases. However, structurally enforcing completeness and quality of data through processes remains a common challenge.

Network models

Network models represent the electrical properties of components (including loads and generators) and the relationships between the components. Up-to-date, correct, and complete network models in the right format are required to perform calculations on the grid in both operations and planning. The format of the models is determined by the software tools used and the type of calculations performed. Often, network operators need to perform various types of calculations, and this introduces the complexity of maintaining and synchronizing multiple sets of models. It makes sense to automate parts of this process and generate



network models by algorithms based on the underlying asset data. However, this calls for even higher requirements on data quality and related processes. Network operators typically already possess models of their networks, but often they are not suitable for large-scale automation, the quality is varying, and the data is incomplete.

Operational data

Operational data include both aggregated records as well as current and historical measurements from the grid. Yearly sums and extremes for consumption and loads are already commonly available. However, significant potential lies in time series data of power flows, loading, voltage, etc. Collecting such time series data requires a sufficient number of sensors, and a set of tools and methods for estimating missing data, such as state estimators and other methods for approximation. This leads to significant flows of data, which need to be correctly ingested, cleaned, and transformed to the right format and units before storing in a data lake.
In transmission, there are typically enough sensors. However, the data quality is often impacted by switching and outages, and the resolution is only sufficient for steady-state analysis. Collecting high-resolution, synchronized data for investigating system dynamics remains a challenge.
On the other hand, in distribution, sensors are not as ubiquitous. Network operators must deal with the roll-out of cheaper sensors or continuous state estimation and the resulting growth in data flows. Smart meters can provide insights in low-voltage networks, but privacy regulations are a limiting factor.

Automated grid calculations and data-driven decisions

Network operators are already using calculations and simulations to make decisions, sometimes also based on automated calculations. However, the scale at which this happens must change dramatically. Worst-case or typical-case types of calculations are not sufficient. Advanced methods going towards probabilistic, stochastic approaches should be increasingly adopted. Data-driven approaches should be adopted in processes across asset management, operations, and infrastructure domains, in planning, scheduling, etc. This will allow for analyzing multiple scenarios quickly and making the right decisions efficiently. Deeper insights with higher resolution in terms of time, assets, and resources are necessary to increase efficiency and utilization across the organization. Therefore, the amount of data used in these processes has to dramatically increase. The availability of external sources of weather data, socio-economic data, geographical data, etc., create new possibilities to improve or completely overhaul processes across the organizations.

Machine learning and artificial intelligence

Data-driven processes can be further enhanced with artificial intelligence and machine learning algorithms. These applications can include the following:

- Short-term forecasting for operational decisions, congestion management, and flexible planning of maintenance
- Mid- and long-term forecasting for investment decisions

- Pattern recognition for detecting theft and market distortions
- Aided and augmented decision-making across the organization.

Unlocking the value of grid analytics

True value gets unlocked only when the levels of the pyramid are built from the bottom upwards and when the quality of the underlying layers is ensured and enforced. Productive operations and consistent delivery of value can be achieved by each level only when the lower levels can be relied upon. For example:

- Good network models cannot be built if the underlying asset data is not in order.
- Operational data cannot be used effectively without good models and correct asset data, as the data will often not make any sense.
- Without high-quality models and operational data, millions of calculations can be run, but they will lead to incorrect implications and wrong decisions.
- It is impossible to operate the grid with the help of advanced algorithms without correct inputs and without having data-intensive, highly automated processes.

Many use cases require large datasets across the whole network and deliver value only after the data quality reaches acceptable levels across the board. Of course, it is advantageous to start experimenting with and piloting solutions across the levels. For this purpose, use cases where a small subset of data is sufficient to deliver value are most suitable.

Data quality is paramount

Data quality issues undermine the value and trust in tools and the results they provide. Therefore, data quality across the pyramid is of vital importance. Processes ensuring the continuous improvement of data quality need to be in place. Employees across the organization must be able to easily report issues and see that the errors are getting fixed at their source.

Organizations around the world have been creating data lakes and often filling them with raw, uncleaned, and sometimes poorly labelled data. This leads to storing a huge amount of poorly usable data. It is necessary to ensure high data quality during the ingestion process, and to store only complete, unified data and allow easy access to it.

Examples of use cases suitable for early adoption

Load forecasting; Renewable generation forecasting	Requires only limited asset data and network topology information, as it relies highly on operational data, weather data, automated calculations, and machine learning algorithms.
Frequency domain calculations	Require very specific and high-quality asset data and network topology information (including its change in time) and automated simulations. Does not rely on operational data or machine learning.
Fraud detection	Relies on subset of operational data, automation, and machine learning algorithms. It requires limited asset data and topology information, often reduced to certain areas.

« Poor data quality makes even good tools and models useless. »

Culture and legal landscape play a role.

Over the past decades, network operators have developed a culture, which is driven by the nature of the business being an asset-intensive regulated monopoly, its main drivers, surrounding stakeholders, and the landscape of laws and regulations they operate in.

Culture

Network operators are running a very specific business – developing and operating infrastructure assets, which must serve the public good now but also for decades to come. The regulator acting on behalf of the society determines the revenue of network operators and to a large degree determines the rules and regulations, and as such it is the single most important stakeholder for every network operator.

Such fundamental dynamics have led network operators to adopt the perspective of large margins of safety. These margins of safety have allowed network operators to accommodate the growth of load, to see potential problems years ahead, and to plan and execute necessary expansions and upgrades in a timely manner. Conservative approaches and a focus on guidelines and processes have allowed a gradual development of stable and reliable power systems, without overly relying on individuals.

As the assets deployed are to stay in place for several decades, decisions do not have to be made quickly, but they have to be the right decisions. The legal landscape further reinforces this, as large-scale outages and curtailment have very harsh financial and reputational consequences. And as explained above, the regulator's satisfaction is of paramount importance for network operators. Although network operators have to adapt to new challenges, it is important to recognize and acknowledge that their culture has served them and the society well for decades. Therefore, these aspects of safety, conservatism, consensus, and a focus on processes became engraved into the culture and the way of working.

As such, the culture in network operators' organizations is largely different than that of popular technology behemoths. Rapid prototyping, disruptive innovation, a "fail fast, fail often" mindset, and generally fast-paced aggressive approaches to solving problems are often in direct contradiction with the culture of network operators and the nature of people working there. Such methods and mindsets might be popular in Silicon Valley, but more often than not they fail to deliver value for network operators.

Therefore, the approach to change and innovation has to be fundamentally different, adjusted to the culture of the organization. Innovation should be gradual and evolutional and should become part of the core processes of network operators. The innovation process should be inclusive, so not driven only by top management and the most innovative individuals. The starting point for every initiative has to be a space of trust, security, and emotional safety.

The emphasis should be on improving standards, guidelines, and processes, as this is the natural way of working for network operators. The user experience of these improved or newly introduced processes should be very good, ideally better than the status quo, to ensure high acceptance and adoption, which is one of the key success factors. By tailoring the approach to innovation in this way, we increase the likelihood that change will not just be accepted by the organization but will also be embraced after time.

Legal landscape

As indicated above, the organization of the sector and the legal landscape have been a major factor influencing the culture of network operators. The current legal landscape consists of EU regulations outlining the core principles, national laws determining the implementation of these principles, and grid codes and other regulator's directives describing the specific requirements and processes.

Although the current legal framework plays a key role in ensuring non-discriminatory access to electrical networks, in fostering international cooperation and market integration, and in introducing fair competition in production and retail activities, it is not without its pitfalls:

- With role separation in the energy value chain and definitions of the obligations of each actor, it is virtually impossible to proactively design the power system in a holistic way.
- Through restricting activities, grid operators have a limited range of investments and measures to take to resolve issues in the grid.
- Connection obligation and investment rules and processes put

network operators in a reactive mode, with limited possibilities to act proactively.

- Rules on equal access and equal pricing cause a mismatch of cost and revenue.
- The cost of curtailment and liabilities in the case of power outages then leads to a very conservative approach to determining capacity.

The European and national legislation brings a solid amount of standardization in governing principles and processes, but a lot remains open to interpretation and negotiation, particularly in areas of approaches to technical analysis, approaches to implementation of processes, the verification of technical parameters and performance, etc. For example:

- What is the available grid capacity and how should it be determined?
- How is grid code compliance verified before and after commissioning?
- How should newly adopted technologies be modeled?

This causes uncertainty for all involved actors and can lead to lengthy negotiations, legal battles, and re-inventing the wheel.

Furthermore, the development, change, and implementation of the new laws and regulations take longer than changes in technology, society, and the economy. As a result, the legal framework often lags behind.

Ways forward.

The world of energy is changing and so are network operators. Over the past years, network operators together with other stakeholders have run many initiatives to address the fundamental trends and the challenges they bring with them. We have seen an improvement in communication between actors in the energy business and the creation of platforms for collaboration. However, much more still has to be done to make the energy transition possible.

Using grid analytics for smarter decision-making will be essential to deal with an increasingly challenging reality in an effective way. The good news is that most of the required technology is readily available. The challenge lies in building and implementing systems, applications, and processes on a desired scale and with the level of quality that spreads trust. It is crucial to build the pyramid of grid analytics from the base up, layer by layer, and to embed processes that will drive continuous improvement in data quality in a highly effective way. The layers and relevant processes should be fully implemented, and the delivery of value should be ensured, before efforts are redirected elsewhere.

Many initiatives and use cases have a somehow twisted Pareto characteristic, with 80% of the value being unlocked with the last 20% of the efforts. Neglecting this gradual buildup and emphasis on completeness and data quality will lead to a failed value delivery and loss of trust in the adoption of data-driven approaches, and in innovation in general. Use cases where partial data is sufficient are excellent for experimentation, building up capabilities, and developing processes and ways of working in the digital domain.

Rapid transformational changes will clash with the culture of network operators and will likely fail due to resistance. Adopting grid analytics should rather come in the form of gradual, evolutionary improvements becoming part of the core processes, perhaps best described as “planned innovation” with almost certain added value. Completing the initiatives fully and ensuring the full unlocking of value is essential for the organization to not only accept change but also embrace it. It is also helpful when use cases are identified from within departments, not just by the management or the most innovative individuals.

A broader discussion on the legal framework is necessary, as well as reconsidering stakeholders’ attitudes toward curtailment, flexibility services, tariff structures, the liability of network operators, and the holistic, proactive management of energy systems. It is also clear that continuing efforts to foster national and international cooperation is vital.

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