ENERGY MANAGEMENT AND FLEXIBILITY IN MOBILE NETWORKS

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ENERGY MANAGEMENT AND FLEXIBILITY IN MOBILE NETWORKS

by NGMN Alliance

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EXECUTIVE SUMMARY

Energy Management is a key issue for operators as they seek to manage costs and integrate renewable energy into their operations whilst continuing to meet demand and users' performance and quality expectations.

In this context, operators need to adopt the right energy management strategies to manage the energy demand on their base station sites in the most sustainable and cost-effective way.

So far, operators have primarily focused on acquiring low carbon energy from the grid and hedging for longer to ensure a cheaper and more stable supply of low carbon energy. In this publication, NGMN presents energy management strategies that take advantage of the opportunities from the energy market allowing operators to reduce their operational costs and even create new value-added services through energy flexibility initiatives (see Figure 1).

This publication provides a consolidated view of the identified benefits of each strategic path, as well as the associated enablers and pre-requisites. The aim is to help operators identify key considerations when making a choice on energy strategy so that the right balance between sustainability goals, investments, and energy cost stabilisation can be achieved.

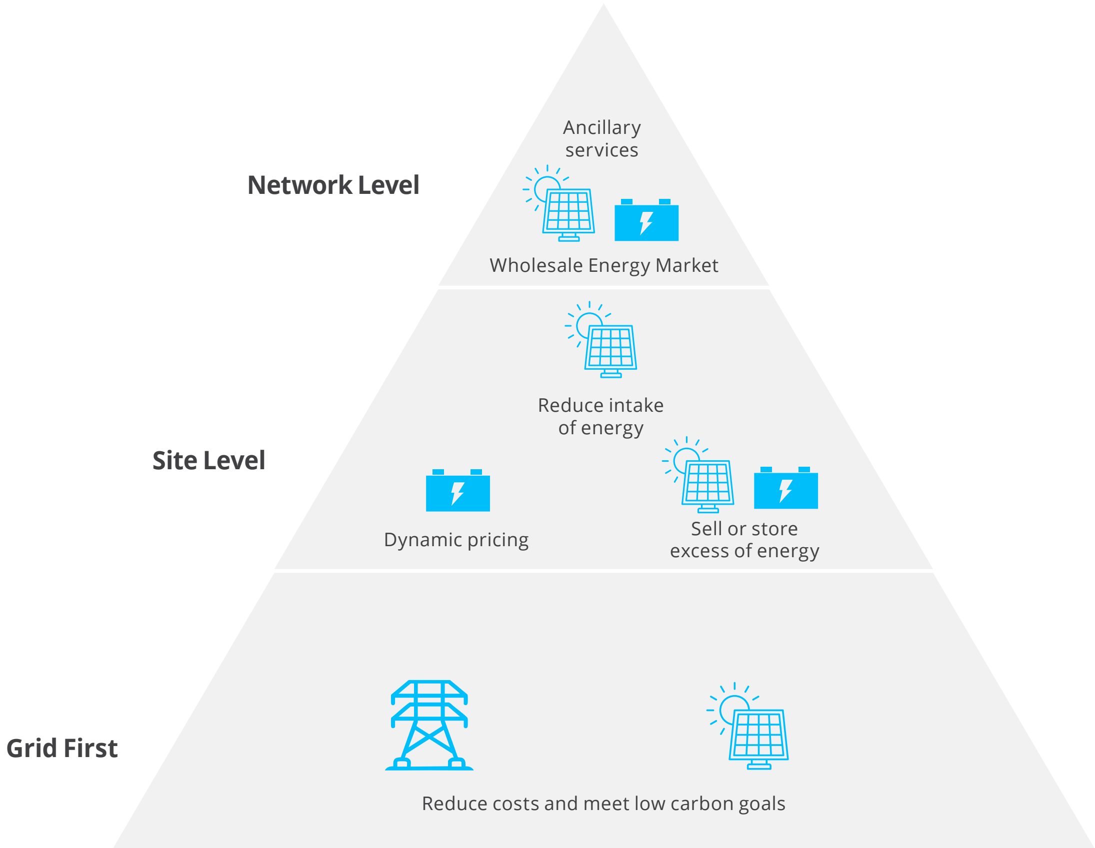


Figure 1 Network Energy Management strategic paths presented in this publication.

The NGMN Alliance makes the following recommendations with a view to advancing this important area of work within the industry and with industry partners.

Planning for the integration of Variable Renewable Energy (VRE)

1. Operators should consider the VRE integration phase in their country when selecting energy management strategies.
2. Strategies where operators rely heavily on the grid to meet their demand for low carbon energy only make sense in countries which are at a more advanced phase of integrating VRE into the grid.
3. Operators must think carefully before investing heavily in their own VRE generation in countries which are already at an advanced stage of VRE integration into the grid.

Energy Management at the site-level

1. Energy Management on a per site level basis must consider the energy sources available (e.g. 'clean' grid energy, local renewable energy, battery), traffic load, and availability and cost of each energy source over time.
2. Operators will need to determine suitable energy management strategies in line with their strategic goals: for example, minimisation of energy costs and/or minimisation of carbon emissions.
3. Energy Management must consider regulatory requirements related to mobile service continuity in the event of power outages.

Role of Network Management and AI

1. Network Management and automation powered by AI will have a key role to play in energy management for MNOs.
2. MNOs must ensure any data ingested from 3rd parties (e.g., weather and energy cost) is verified and trustworthy with procedures in place to rapidly recover from faulty data.
3. Due to the critical nature of mobile networks – whereby they are often designated as of national importance – MNOs must be aware of and be able to demonstrate to regulators that any AI developed and deployed to manage energy will do so within acceptable limits for network availability and network performance. The industry should study how such transparency can be (independently) verified.

Energy Flexibility and the role of MNOs

1. Energy management systems shall be capable of rapid reaction to external triggers not initiated by the element management system but from an external source.
2. On-site energy management systems (e.g. site controller) must fulfil regulatory requirements for the energy flexibility market.
3. Demand response service providers must comply with evolving national legislation, while MNOs' internal security guidelines must be fulfilled by their service providers.
4. To maximise the potential for Variable Renewable Energy the mobile industry should work with the energy industry to achieve a suitable standardisation and regulatory environment that encourages harmonisation.

INTRODUCTION

The NGMN Green Future Networks Programme delivers leading telecoms industry guidance towards energy efficient operations and a sustainable economy. This publication outlines and prioritises the various energy management options available to operators to meet the energy demands for their networks.

- Chapter 2 introduces the evolving energy landscape together with the associated challenges and opportunities for operators.
- Chapter 3 presents a potential energy management roadmap with strategic intent and introduces the energy market, its actors, and services.
- Chapter 4 presents pre-requisites and enablers to help operators implement energy management strategies and participation in the energy flexibility market.
- Chapter 5 presents energy management strategies for base station sites together with results from trials in real network deployments.
- Chapter 6 focuses on large-scale solutions as well as considering the interactions between the telecoms network and the energy market.
- Finally, Chapter 7 introduces the most recent key learnings from NGMN's Green Future Networks Programme on energy management, highlighting the potential gains of the solutions presented in this publication.

02 CHALLENGES AND OPPORTUNITIES FROM RENEWABLES AND A FLEXIBLE ENERGY MARKET

As the energy landscape shifts towards decentralised renewable systems, telecoms operators face unique challenges and opportunities in managing their networks' power needs. This transformation presents a complex interplay of technological, economic, and environmental factors that will shape the future of telecommunications.

The primary challenges facing MNOs in this evolving energy landscape are threefold. First, ensuring energy security and resilience has become increasingly complex. Operators must grapple with fluctuating energy availability, continued reliance on grid power and the need to maintain network resilience during energy shortages. These factors combined make it difficult to guarantee a stable power supply for communication systems.

Secondly, economic hurdles pose significant obstacles. The high costs and long time for return on investment to materialise associated with distributed renewable energy facilities strain operators' budgets. Additionally, volatile energy prices driven by geopolitical tensions create financial unpredictability. Operators without adequate energy demand and pricing forecasting tools may face increased costs, further complicating their economic outlook.

Lastly, the integration of renewable energy sources presents its own set of challenges. The intermittent nature of renewables complicates network operations management. Limited transmission infrastructure for sourcing Variable Renewable Energy (VRE) and the need for increased investment in storage and VRE generation add layers of complexity to the transition towards sustainable energy solutions.

Despite these challenges, there are significant opportunities for operators. Sustainable energy management emerges as a key area for innovation and cost reduction. By optimising energy use through flexible management strategies, investing in energy-efficient networking equipment and IoT solutions, and maximising low-carbon energy usage, operators can meet CO2 targets while potentially lowering operational costs.

Furthermore, this transition offers chances to enhance network resilience and drive innovation. Strategic investments in resources can improve service quality in the changing energy landscape. Leveraging AI and IoT for real-time monitoring and efficient energy management not only optimises operations but also opens doors to new business opportunities in energy management and grid stability.

Finally, operators have the potential to actively participate in the evolving energy market. They can develop energy storage solutions for grid support, potentially contribute VRE supply to the grid using available real estate and optimise network power costs through smart energy demand tracking and pricing strategies.

While the energy transition presents significant challenges for telecom operators in balancing network reliability and sustainability, it also offers unprecedented opportunities to innovate, reduce costs, and create new services.

03 OVERVIEW OF ENERGY MANAGEMENT AND THE ENERGY MARKET

NGMN have identified three main strategic paths that can be adopted by operators for energy management: grid first, site level, and network level strategic paths.

The grid first strategic path focuses on operators' ability to secure low carbon and renewable energy from the grid for their network in a cost-effective way and to manage their costs against fluctuating energy pricing. Various options exist on the market for MNOs to purchase electricity from suppliers (e.g. negotiated contracts; Power Purchase Agreements (PPAs)). MNOs can also invest in energy production projects. Each MNO must make its own decision on the optimal approach to secure low carbon and renewable energy from the grid.

The site level strategic path delivers on site Distributed Energy Resource (DER) management so that operators can optimally use the multiple sources of energy available on site to maximise the use of low carbon and renewable energy whilst reducing the energy cost. This strategic path requires operators to deploy new infrastructure in the form of battery storage and/or VRE generation where there is real estate available on site. Operators use the batteries to store off-peak tariff energy, together with policies/guidelines to carefully manage how the stored energy is used during peak tariff periods to meet the site energy demand or to implement peak shaving in the energy requirement from the grid during periods of peak traffic. Battery storage can also help operators to offer excess capacity for ancillary services to 3rd party aggregators, e.g., Virtual Power Plants (VPPs) (see Sec 3.1.3.3 and Sec 6.1.2) or use excess capacity for Demand Response (DR) services (see Chapter 3.1.3.2 and Chapter 6.1.2) via 3rd party aggregators.

With infrastructure for VRE on site, renewable energy is generated and used through distributed power systems in individual cell sites or groups of sites, and its excess is stored in batteries. This reduces operator's intake of energy from the grid but does not eliminate it. Depending on local regulations, operators can also feed excess generated VRE directly to the grid or to an aggregator.

The network level management strategic path focuses more specifically on helping operators to fully exploit the infrastructure they have deployed on their base station sites. In fact, operators may intentionally dimension the VRE and storage infrastructure on their site beyond what is needed for site consumption. This strategy is based on the agglomeration of the capabilities deployed in distributed sites so that MNOs can become viable players in the energy market.

Therefore, if any operator decides to play such a role (and if local regulations allow) it is a pre-requisite for operators to act as a VPP or become a viable energy supplier to a VPP. Operators can aggregate and sell excess energy to the wholesale market or participate in the energy stock exchange. They can further aggregate excess capacity and sell it as ancillary services to a Transmission System Operator (TSO) or a Distribution System Operator (DSO) or manage the excess capacity and sell as DR services to TSO/DSO (see Chapter 3.1.2). Network level management strategies are typically based on real-time exchange of data between the telecoms and beyond-telecoms ecosystems to allow participation in the energy flexibility market, a topic of growing interest within the MNO community.

Table 1 summarises the three main strategic paths for energy management. In the following table,

- ‘Active participation’ implies the operator has some energy generating/storing resources or has investments in energy generating resources
- ‘Consumer only’ implies the operator only consumes energy from the grid

Table 1. Strategic paths for Network Energy Management

Path	DERs	Participation Approach	Primary Resource Type	Strategy Summary
Grid First	N/A	Passive participation	Grid	• Achieve cost reduction and manage cost variability through negotiated contracts (e.g. PPAs). • Increase use of Renewables by sourcing low carbon grid en
	Off-site	Active participation	VRE production	• Invest in green power plants (to further ensure sufficient access to VRE).
Site Level	On-site		VRE production	Reduce grid intake during periods of VRE production
			Battery storage	Store excess VRE to reduce grid intake to a minimum
			VRE production	Offer excess energy to 3rd party aggregators
			Battery storage	• Lower costs through buy now, use later. • Offer excess battery capacity for ancillary services • Using excess battery capacity for DR services
Network Level			VRE production	Aggregating excess generated energy and offer new energy services to energy markets
			Battery storage	• Participate in energy markets • Aggregating excess battery capacity and offering it to TSO/DSO (ancillary services) • Managing excess battery capacity and offering it to TSO/DSO (DR services)

In the rest of this chapter, we introduce the status of the energy market, the concept of energy flexibility together with the key actors and roles of the energy flexibility market. In the next chapter, further consideration is provided on key enablers relevant to help operators realise energy management strategies and enable energy market participation. Subsequent chapters treat the different strategies in more detail.

3.1 ENERGY MARKET

Within the energy market, a large variety of companies organise the production, trading, marketing, transmission and supply of electricity. It is vital for any society to have an electricity market that ensures sufficient availability and affordable prices for private (retail market) and business customers (wholesale market). This is the field of work of national and international regulatory bodies.

As renewable energy sources become increasingly integrated into the energy system, flexibility has emerged as a crucial element for ensuring stability and security of energy supply. Energy flexibility refers to the ability to adjust power generation and/or demand in response to varying electricity prices, market changes, and transmission and distribution system conditions. MNOs have an opportunity to leverage their resources, such as battery storage and connection to the grid, to participate in flexibility mechanisms, yielding environmental benefits and providing new value-added services.

3.1.1 Energy Flexibility Market Potential

The flexibility market is experiencing significant growth, driven by the increasing integration of renewable energy sources. A European Union Agency for the Cooperation of Energy Regulators (ACER) report indicates that the share of Renewable Energy Sources (RES) in the European energy mix is expected to rise dramatically [1], necessitating flexibility solutions to manage this variability (see Figure 2).

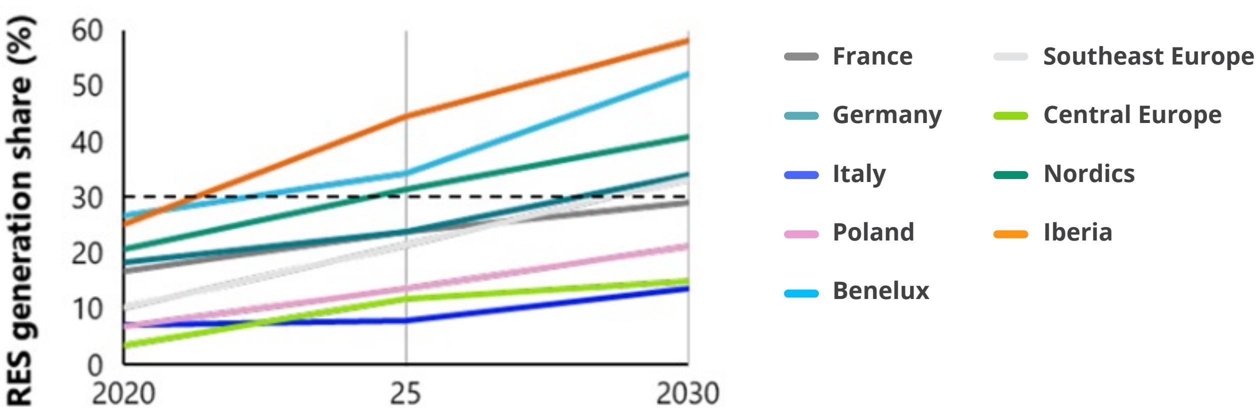


Figure 2. Projected electricity generation from intermittent renewables by country or market [2].

The 2024 International Energy Agency (IEA) document on implementing COP28 energy goals highlights the same need for enhanced system flexibility, particularly through energy storage [4]. Additionally, factors such as the increasing electrification of industry and transport are contributing to this demand for storage solutions.

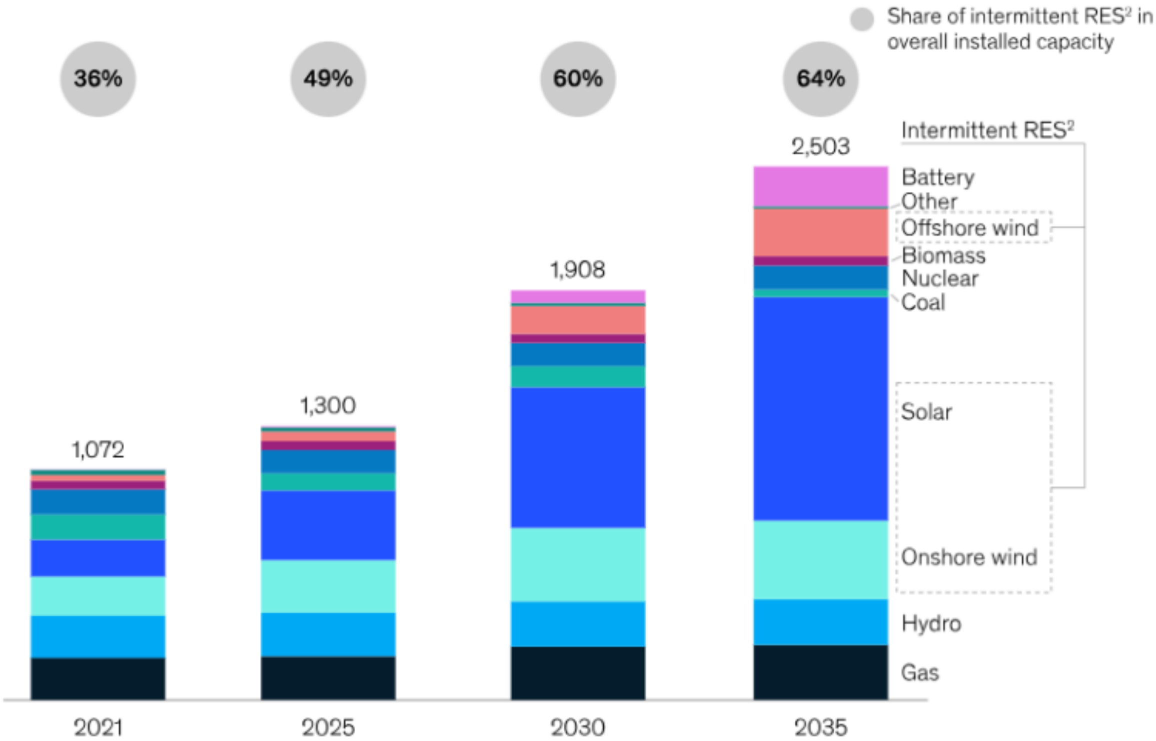


Figure 3. Installed capacity [Gigawatts] in main European markets under accelerated energy transition [3].

Figure 3. Installed capacity [Gigawatts] in main European markets under accelerated energy transition [3].
To achieve the COP28 targeted global renewable energy capacity by 2030 while maintaining electricity security, energy storage needs to increase six-fold [5]. At the same time, as more intermittent sources like wind and solar are integrated into the grid, the demand for flexibility becomes critical to ensure grid stability and reliability. Depending on the timeline perspective, there is currently a range of possible mechanisms that facilitate the provision of flexibility services (see Figure 4).

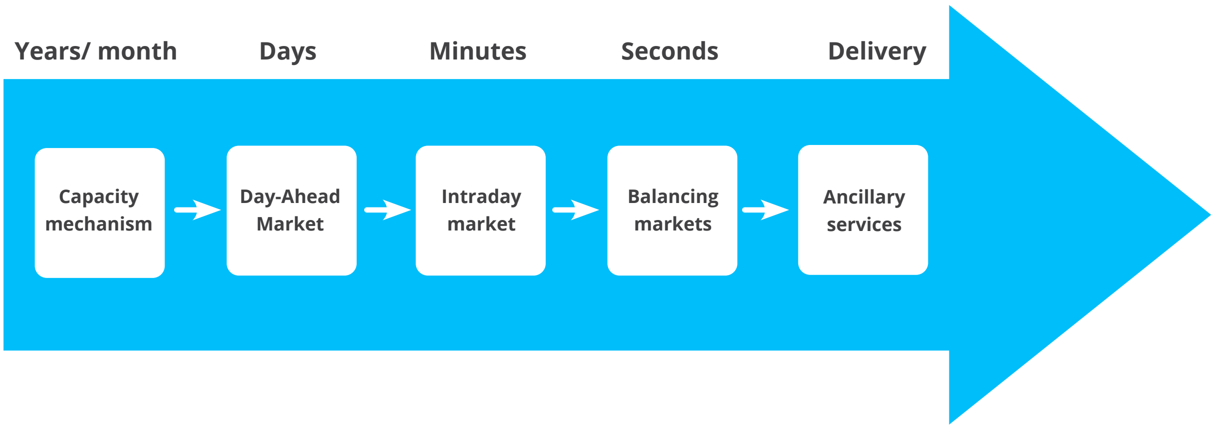


Figure 4. General timeline of European electricity markets/mechanisms

3.1.2 Actors and Roles of the Energy Flexibility Market

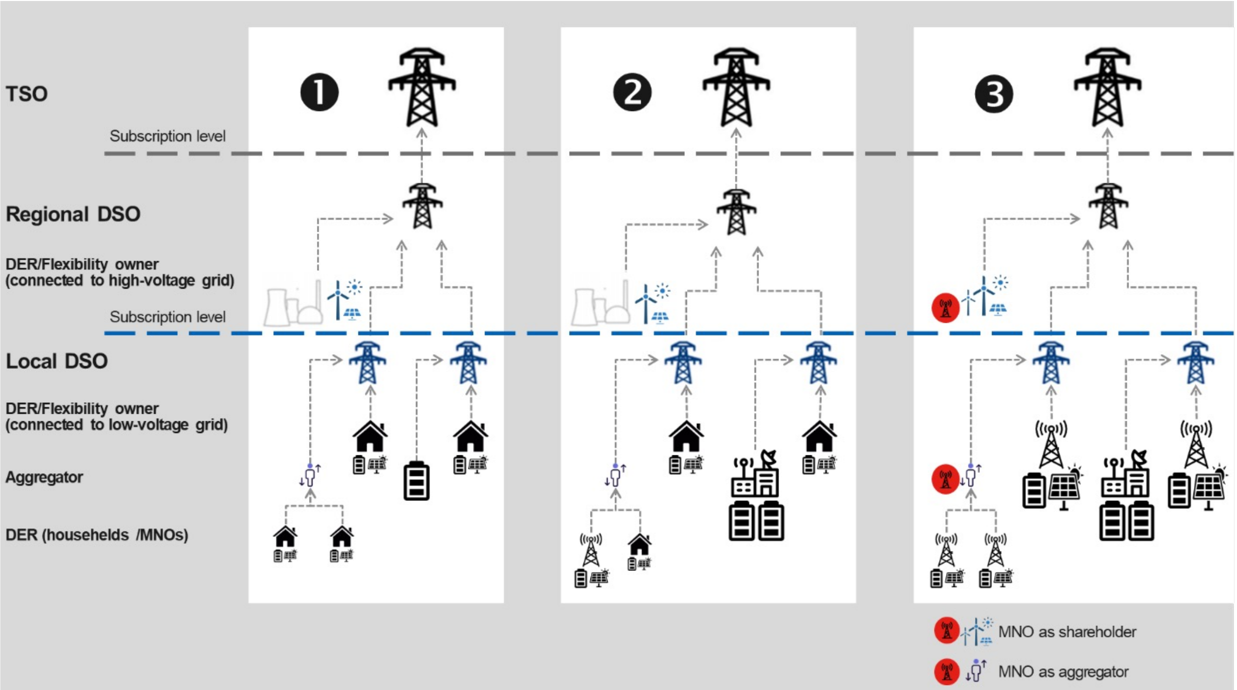


Figure 5. Stakeholders of an example Energy Flexibility Market.

Figure 5 shows the main stakeholders in the energy flexibility market and highlights the possible roles of MNOs in this ecosystem.

- **Transmission System Operator (TSO):** Oversees the transmission of electricity from generation sites to regional distribution networks.
- **Regional Distribution System Operator (DSO):** Manages the distribution of electricity within a region, ensuring reliable supply to local DSOs.
- **Local DSO:** Manages the distribution of electricity at the local level, connecting to end-users.
- **Distributed Energy Resources (DER)/Flexibility Owners:** Own and operate distributed energy resources, providing flexibility to the grid.
- **Aggregators:** Collect and manage DER to provide flexibility and balance supply and demand.

In the left side of Figure 5 (1), we can see the traditional energy distribution system without MNOs as participants. The middle of the Figure 5 (2) shows the MNO as owner of DERs at various Telco sites (see Table 1, active participation) thus providing flexibility to the grid. In the right side of Figure 5 (3), MNOs can act as an Aggregator (see Table 1, active participation) collecting and managing its own DER to provide flexibility and balance the grid. [1]

1. As there is no global energy market, there may be different definitions of processes & roles of actors (e.g. transmission and distribution networks are very often distinguished by different voltage numbers) based on different regulatory associations and historically grown infrastructure.

3.1.3 Energy Market Types and Flexibility Service Types

The energy market is supposed to balance energy demand and production. Day-ahead and intraday are the periods when forecasts are most likely to match reality. To ensure a reliable supply of energy even during short-term imbalances, specific flexibility services keep frequency, voltage and power load within certain limits. This makes the short-term spot market and related services an essential tool for balancing the overall system.

3.1.3.1 Energy Market Types

The energy market relies mainly on a long term – price stable – and a short term – flexible - component. Any regulation that integrates environmental sustainability goals into the market has to define specific regulations to integrate highly flexible, renewable energy sources into the market.

Wholesale Market – PPAs:
A PPA often refers to a long-term electricity supply agreement between two parties, usually between a power producer and a customer (an electricity consumer or trader). The PPA defines the conditions of the agreement, such as the amount of electricity to be supplied, negotiated prices, accounting, and penalties for non-compliance. Since it is a bilateral agreement, a PPA can take many forms and is usually tailored to the specific application. These trades take place outside of power exchanges without intermediaries or clearing houses. Trading partners are in direct contact with each other or make use of a broker. PPAs may also have short term components (day-ahead and intraday).

Wholesale Market – Spot market: With increasing contribution of renewable energies to the total energy mix, the energy exchange markets will gain more importance. This makes the short-term spot power market an essential tool to balance the overall system. And since the European spot power markets are coupled, they help to provide electricity where it is needed and when it is needed. Currently, efficient wholesale markets are a prerequisite:

- to fill up demand gaps, if long term PPAs are not sufficiently covering the short-term energy demand of Significant Grid Users (SGUs) and
- to generate competitive retail markets.

The prices of VRE depend on the availability of the constituent renewables in the VRE mix (see Figure 6). As the proportion and prevalence of renewable energies increases, the volatility of prices may intensify. Once the legal, procurement and technical (see Chapter 4.3) pre-requisites to benefit from the energy exchange market are installed, operators can offer new services around idle capacity by buying energy in off-peak price periods and buffer it in, say, batteries to discharge energy during the high-price periods to avoid the “simultaneous high price – high demand trap”.

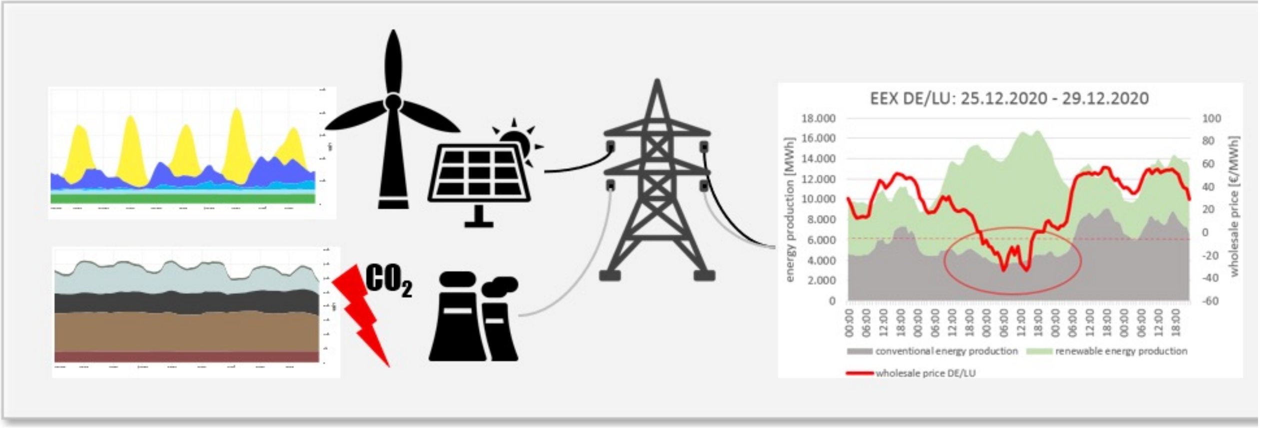


Figure 6. Adding renewable energies into power supply (top-left side of the figure) causes strong fluctuations of energy prices (see the graph) related to the weather condition.

3.1.3.2 Flexibility Service Types

Market aggregators can offer ancillary and DR services to TSOs for balancing and congestion management. Participants of these services can bid in advance for availability and can receive compensation for reserve services, subject to pre-qualification requirements.

Demand Response (DR) services are provided under the umbrella term of DSM by energy utilities that incentivise users to adjust their power consumption to align with available electricity supply. The focus of DR services is on activities that reduce or shift electricity demand in response to real-time events on the grid, therefore addressing short-term fluctuations in demand or supply. Typical DR service levels are “Peak power limit” and “Peak load limit”, together with a validity period (i.e., the time window for providing the committed service level).[2]

DSOs and TSOs can improve efficiency and manage congestion, potentially deferring grid reinforcement costs. Current tariffs can reward customers based on demand response, usage type, time of use, capacity, and carbon emissions.

Ancillary services: In general frequency and voltage are the parameters that become unstable in a transmission and distribution network due to the mismatch of energy production and consumption. Power utilities may signal demand requests to their customers and batteries can be used to stabilise the power grid by quickly responding to fluctuations in grid frequency and grid voltage.

Flexible energy markets are constantly evolving, and balancing services are currently being implemented in a way that could be of interest to mobile operators. Typical ancillary service levels are "capacity demand" and "frequency threshold" (whose measured value triggers requested power input to the grid or requested consumption from the grid) together with a validity period (i.e., the time window for providing the committed service level).

“Control reserve” is the energy deployed to compensate for unforeseen power fluctuations in the electricity grid. Control reserve may be positive or negative. The use of balancing power can involve both feeding and withdrawing power from the grid. Mobile network operators can contribute by charging or discharging batteries used on site.

2. This publication focuses on frequency instability / frequency balancing, as the market is most mature in terms of implementation and competition.

The TSO buys capacity for this control reserve, while aggregators must provide a minimum capacity reserve according to national regulations in many electricity markets.
The provision of ancillary services is a complex process (see Figure 7):

- **Prequalification:** Potential balancing service providers must provide proof that they meet the technical requirements for the reservation and activation of the different control reserve qualities in a pre-qualification process in order to gain access to the balancing markets (see Chapter 5.2).
- **Dimensioning:** The transmission system operators (TSOs) calculate the control reserve to be reserved annually and in coordination with each respective energy market stakeholder.
- **Tendering & Awarding:** Tendering, submission of bids and informing providers on awarded contracts or rejections take place via a joint procurement platform. Procurement of control reserve products takes place across control areas (see Chapter 6.2.2). Providers that are awarded contracts commit to hold the offered balancing capacity on standby for potential activation. They receive remuneration for holding the capacity in reserve and - in case it is requested - also for activating balancing energy.
- **Activation:** Only control reserve from providers whose bids for balancing energy have been awarded will be activated.
- **Settlement:** Remuneration for reserving capacity is always a payment by the TSOs to the balancing service providers. Remuneration of activated balancing energy takes place depending on the direction of activation and the energy price as a payment (credit note) or claim by the TSO towards the balancing service providers. The billing process is based on the modalities between the 2 parties.

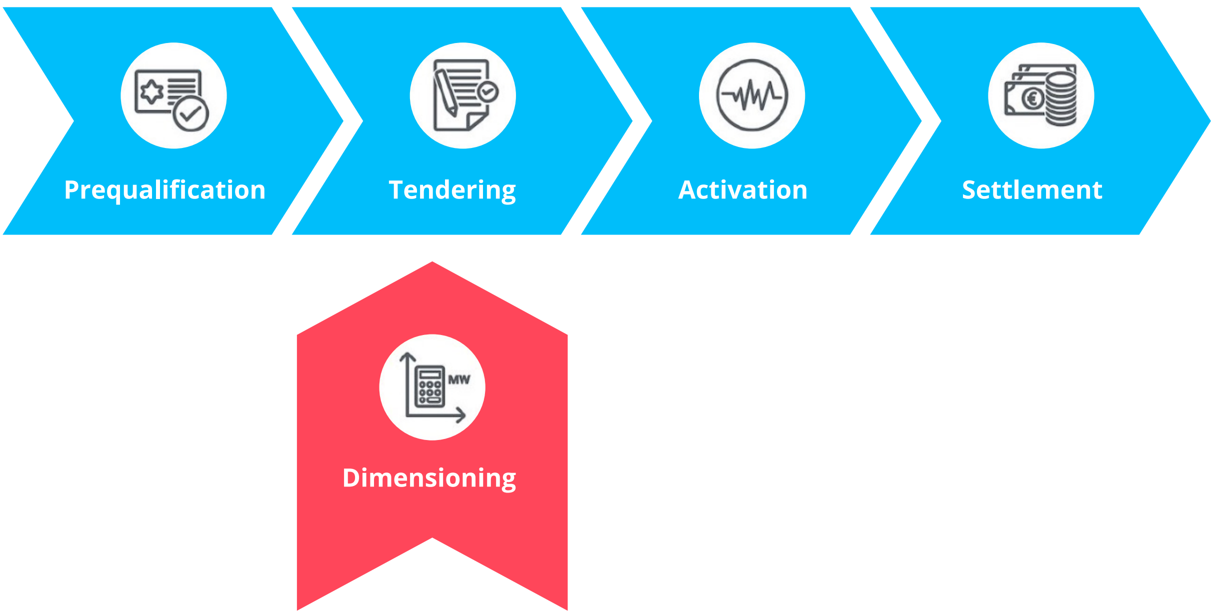


Figure 7 Exemplary process for provisioning ancillary services.

3.1.3.3 Virtual Power Plant

Prosumers can engage in the energy market through aggregators or electricity providers as VPPs to buy or sell energy. In a VPP, DERs are linked to a centralised control system operated towards the energy market by an aggregator. When integrated into a VPP, the power and flexibility of the aggregated assets (DERs) can be traded collectively. Thus, even small units get access to the energy flexibility market (like ancillary services for frequency balancing) that they would not be able to enter individually.

"Aggregators" of VPPs can act as ancillary and DR service providers (i.e. third party/aggregator, see Figure 5). They can also buy the excess renewable energy from DERs and sell it to the wholesale market via PPAs to other SGUs or to the energy exchange. An operator may act as an aggregator itself or as a supplier to a VPP, depending on the strategic decision (see Chapter 4) and the technical and legal possibilities (see Chapter 5). ITU-T standard L.1384 contains a description and solution of radio mobile site usage for frequency regulation as a Virtual Power Plant (see Figure 8) [6],[3] which is structured into three distinct layers:

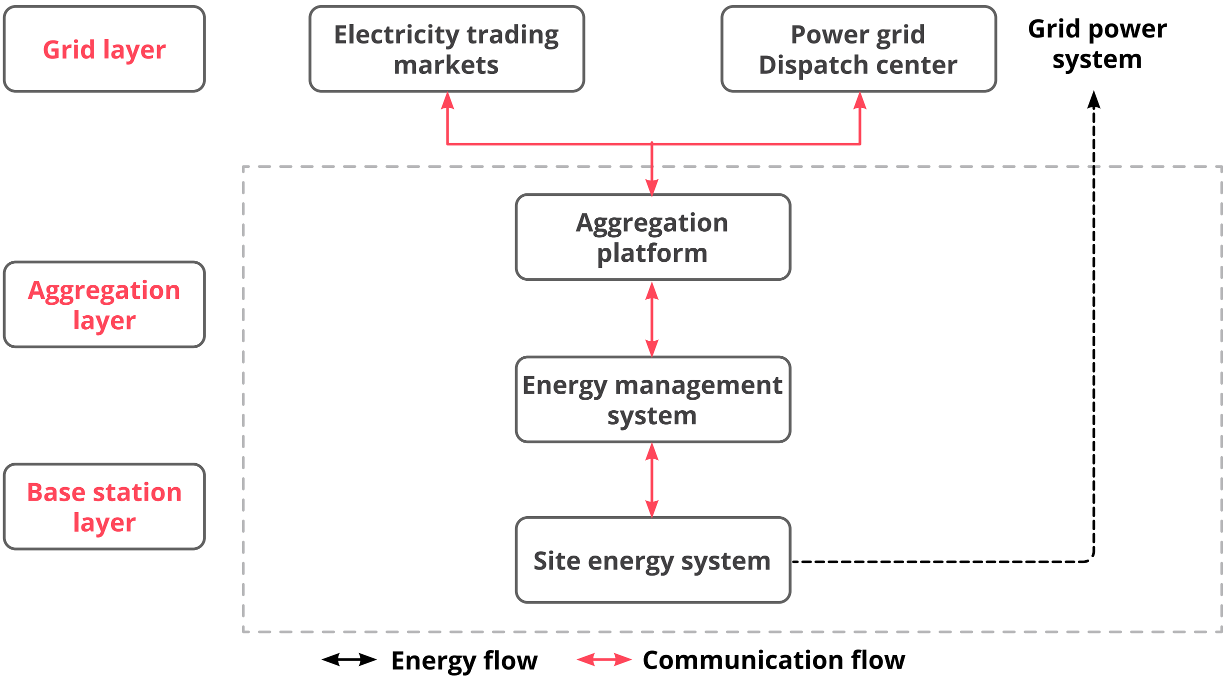


Figure 8 (© ITU): A solution for a VPP architecture from ITU-T standard L.1384 [6].

Grid Layer: This includes a dispatch centre and an electric trading market for the power grid.

- The electric trading market determines energy prices in real-time.
- The power grid dispatch centre ensures grid stability by implementing policies for frequency regulation and load management, overseeing the necessary controls to maintain stability.

3. In some countries mobile networks are seen as "critical infrastructure". Therefore, the connection to a unified control system operated by an external "aggregator" may be prohibited.

Aggregation Layer: This layer aggregates distributed radio base station sites and manages the coordination and control of the base station management systems.

Base Station Layer: Comprising multiple base station sites, this layer houses the site energy systems and its management systems. Each base station site includes various equipment and associated energy infrastructure.

3.1.4 New Value-Added Services for Mobile Network Operators

MNOs have the potential to enhance their service offerings by leveraging existing resources through innovative energy flexibility initiatives. By participating in flexible services, MNOs can provide new value-added services without the need for significant external support.

Grid operators incentivise users who contribute to grid stability, and MNOs could tap into this by offering Demand Side Management (DSM) services. These services would allow MNOs to optimise energy procurement by adjusting supply timing, thus enhancing their operational efficiency. Additionally, ancillary services can generate income by supplying energy or capacity to the grid, enabling MNOs to access favourable market conditions.

MNOs can also explore energy storage solutions to manage price fluctuations in the energy market. This approach not only enhances service offerings but also supports a sustainable energy ecosystem, particularly as demand for battery storage is projected to rise in the coming years (see Figure 9).

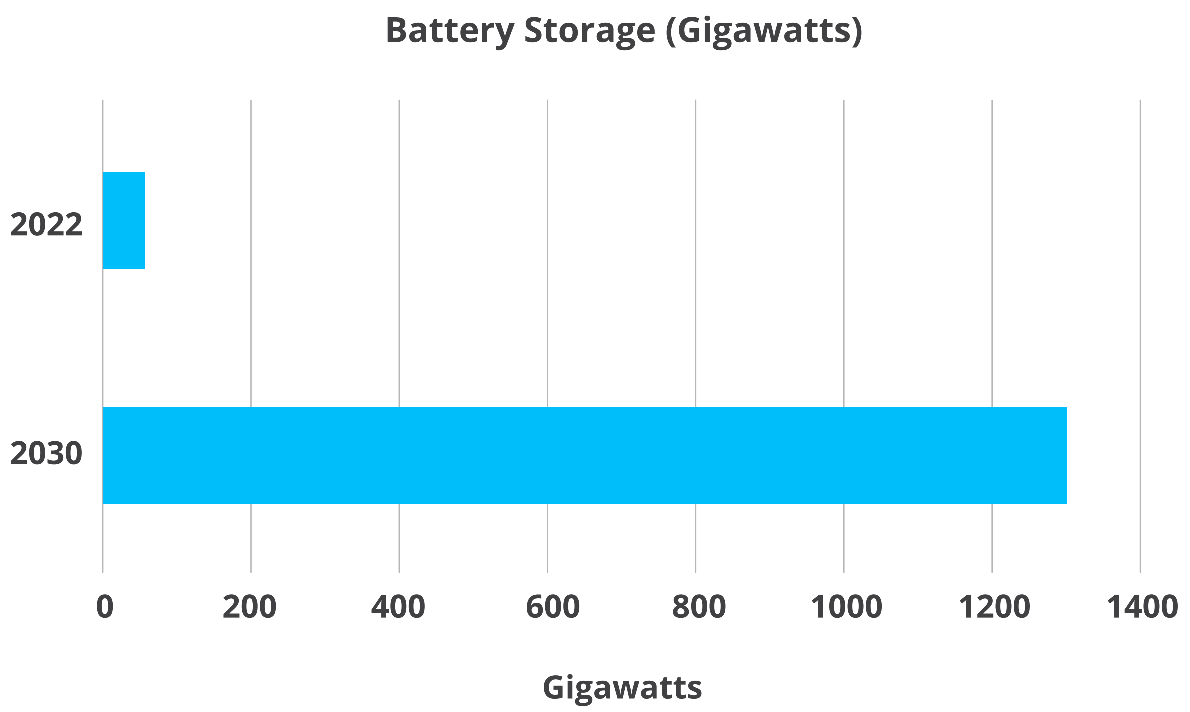


Figure 9. Installed battery storage to meet COP28 target by 2030 [4].

Key aspects influencing the value of flexibility for MNOs include:

- Existing battery utilisation in telecoms services, which can be scaled up.
- Cost reductions in energy procurement through flexibility services.
- Opportunities for quicker returns on investments.
- Potential for new business cases, such as storage investments.

The synergies between flexibility and MNO operations could lead to benefits:

- Combining battery storage with on-site renewable energy generation (e.g., solar and wind) can reduce carbon footprints and support sustainability goals
- Increased battery capacity enhances energy supply resilience while opening avenues for offering new services towards the energy market

By focusing on these new value-added services, MNOs can not only improve their operational capabilities but also contribute positively to the stability and sustainability of the energy system.

04 CONSIDERATIONS FOR ADOPTING ENERGY MANAGEMENT STRATEGIES

Energy management for MNOs implies finding continuously the most cost-effective solution for their energy needs through wholesale agreements on low carbon and renewable grid energy, exploiting opportunities available for renewable energy production on their sites to a maximum and steering the battery charging and discharging in a way that MNOs can buy the energy they need, when it is cheapest.

For operators intending to offer services based on their distributed energy resources by participating in the flexible energy market, energy management will further extend beyond site level management to network level management with an objective to aggregate the distributed energy resources to a level where they can become a viable supplier for aggregators. In this situation, the site level operational management system must be connected to the energy market information data system (see Chapter 6.1).

4.1 ENABLERS AND PRE-REQUISITES FOR ENERGY MANAGEMENT STRATEGIES

For an MNO to realise the energy management strategies identified in Chapter 3, several enablers need to be in place, as well as some pre-requisites which would make adoption of a particular strategy feasible.

In the following figure, we provide a brief overview of what those pre-requisites and enablers are for each of the identified strategies.

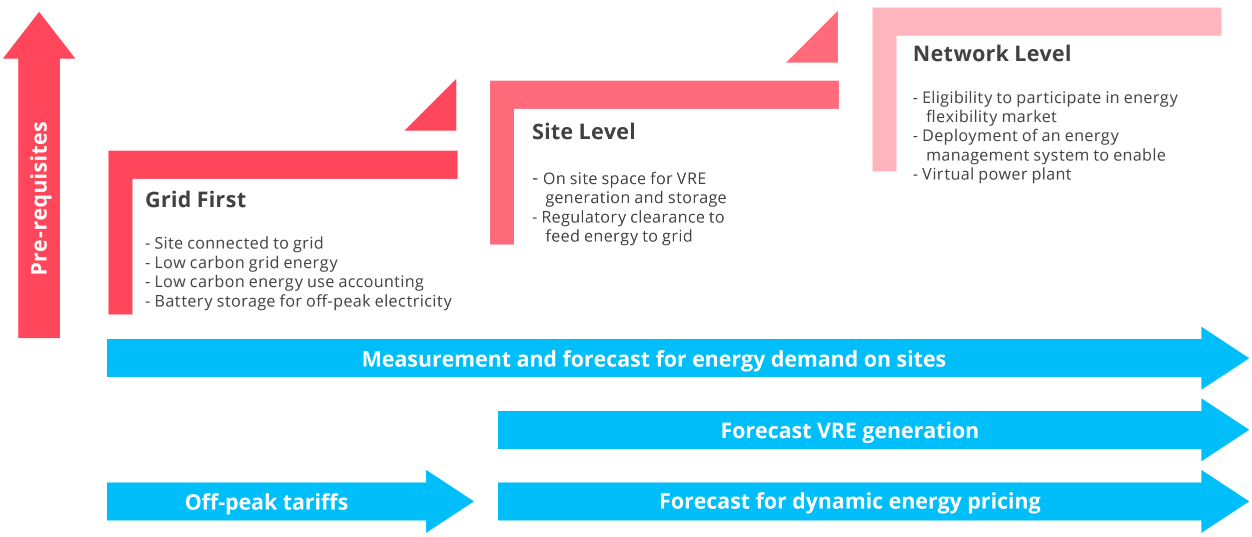


Figure 10. Overview of pre-requisites and enablers of the energy management strategies discussed in this publication.

4.2 FORECASTING CONSIDERATIONS

As a baseline, operators will need to choose an energy management strategy that considers the overall forecast in energy demand for a site, the technology migration strategy and any relevant regulatory constraints. However, to meet the energy demand in the most cost effective and environmentally sustainable way, there are typically three variables for operators to take into consideration when making a choice on the best energy management strategy (see Figure 11):

- Variation of the peak traffic demand (and hence energy usage) at the base station site;
- Variation in the availability and cost of low carbon energy from the grid;
- Variation in VRE generation potential on a base station site or other centralised operator site, which in turn depends on climatic conditions prevailing at those sites and the space available at the sites to deploy VRE infrastructure.

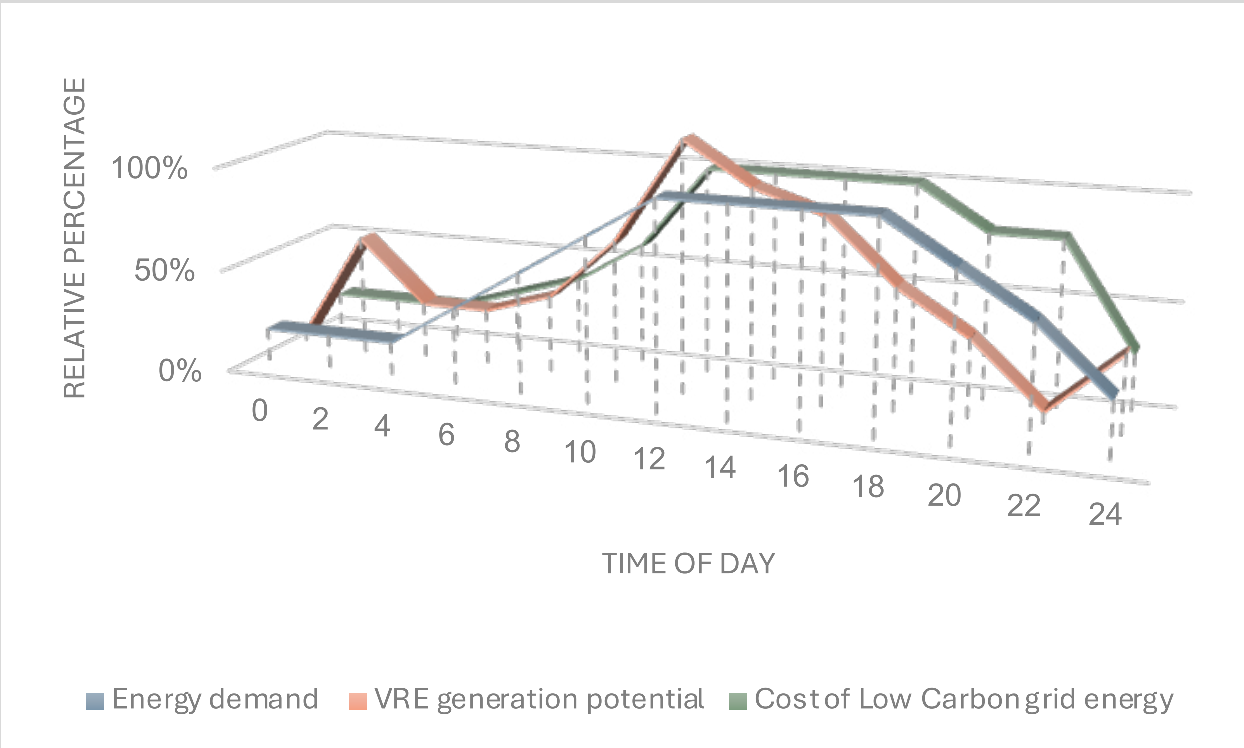


Figure 11. Illustrative view of variables for site energy management.

The main challenge operators have is that periods of peak demand on a site may not always coincide with periods of availability of low carbon and cheap energy from the grid and/or coincide with periods where peak onsite VRE generation occur. Operators will need to do a careful site by site evaluation against those variables to come up with the best energy management solution for the site based on the most accurate prediction of consumption, renewable energy production and information about day-ahead energy prices as well as the demand for battery capacity supply ancillary services (see Figure 12).

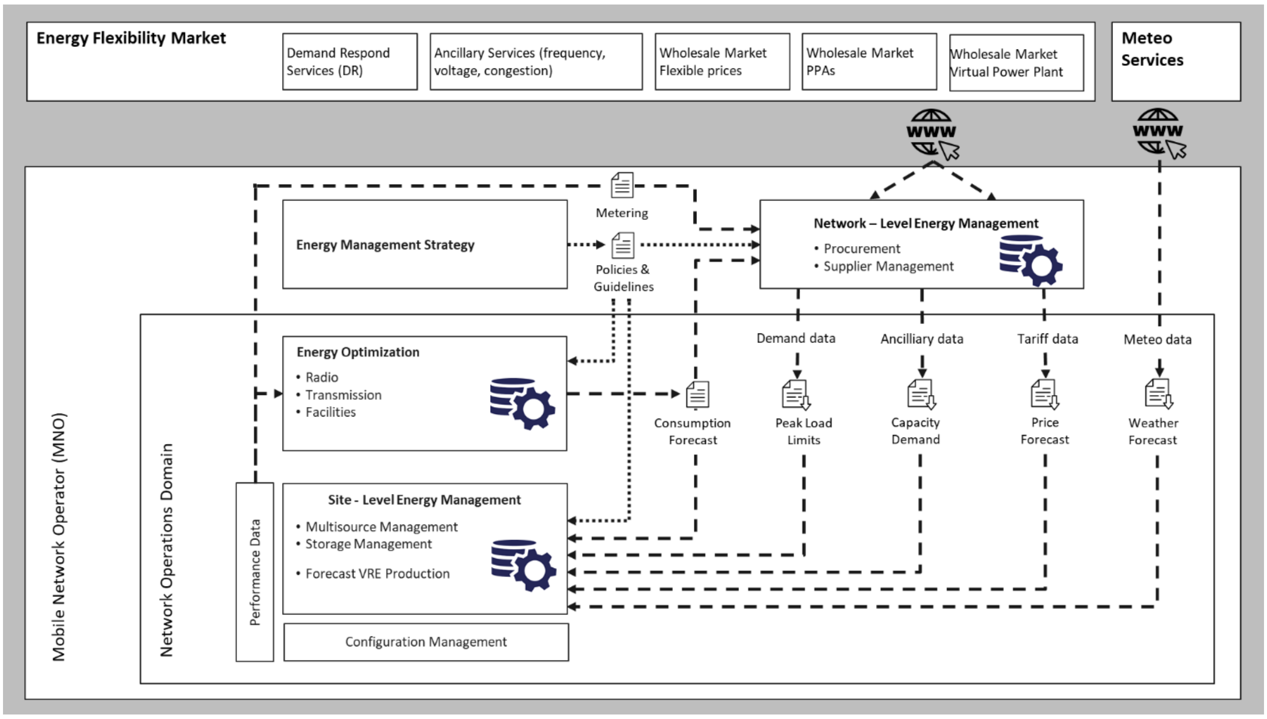


Figure 12. High-level technical view of interaction between energy flexibility market and MNO.

Another challenge faced by operators is that the data they need typically come from multiple sources (telecoms and non-telecoms systems) and data from all of these sources need to be processed in near real time so that the right action i.e. choice of the right source of energy is consistently made according to the operator's optimisation objective such as cost and/or reduction of emissions.[4] The emergence of AI-based data analysis could help operators in this complex task.

The evaluation is further complicated with evolving network deployment architectures and topologies for 5G. If the number of small cell sites were to increase, this could contribute to increased energy consumption. There may also be an increased likelihood of operators having macro sites with energy demands that exceed the available AC grid capacity at a site that may require a grid upgrade to support peak demand.

4.2.1 Forecasting Site Energy Consumption

The main energy consumers at a BS site are facility, transport and radio equipment. Their power consumption is either driven by mobile traffic they handle or by local environmental conditions (e.g. outdoor temperature for air condition). Specific energy optimisation tools will manage the energy efficiency of the related facility, transport and radio equipment according to operator-specific policies including usage of energy saving features such as sleeping modes or bandwidth adaption, among others.

These energy optimisation tools will also be capable of predicting the energy demand (energy consumption forecast), based on measured patterns while also including any perturbations to the normal trend due to known scheduled events and planned equipment configuration changes. AI-based simulations combining all this information to predict the energy demand are already under development. To support the on-site energy management with 24h or 48h forecasts a prediction interval of 60 minutes (in future this may reduce to 15 minutes) should be suitable.

4. Importing data from the external systems into the operational area of MNOs, tower companies or energy serving companies requires careful consideration of security, reliability, and data integrity. This becomes even more important when mobile networks get the status of critical infrastructure with still higher obligations. CAPIF (Common API Framework) plays an important role in securely transferring data from the public internet into a secure zone. By using CAPIF, organisations can create a standardised, secure, and controlled pathway for importing external data. The implementation of CAPIF based exchanges of files is operator specific.

Figure 13 shows the variability of site equipment power consumption over the course of a typical week, which an energy optimisation tool could be able to predict.

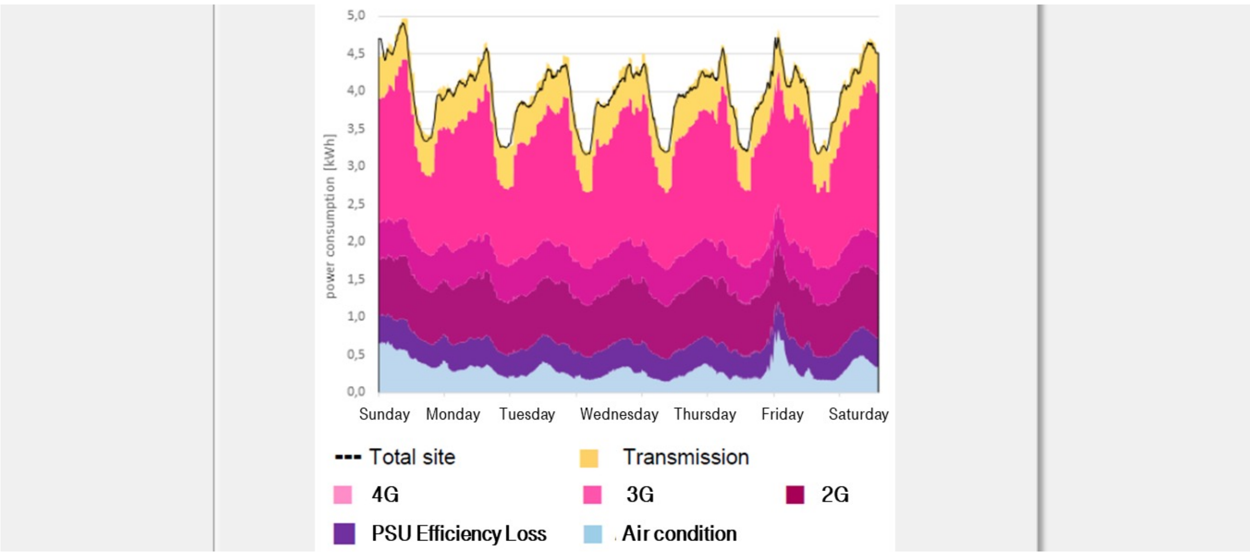


Figure 13. Exemplary power consumption of a BS site in Austria including air condition.

4.2.2 Energy Price Forecast

“Network level energy management” involves scanning the market on a day-ahead basis and deciding from which provider the electrical energy should be bought. This results in one price forecast (see Figure 14). The typical forecast period is 24h based on 1h-values. A further reduction down to an interval of 15 minutes should be considered. Energy prices show yearly and seasonal changes, or jumps triggered by regulatory or geopolitical events. Intraday price swings can be significant, often in the range of 5% - 20% or even more (prices for energy might become negative!). The definition of “high” and “low” prices per day must be flexible. A classification based on policies should be made automatic and autonomous by a model. The definition of “high” and “low” price windows determines battery charging and dis-charging processes. This model should be trained continuously.

In case the operator has a supply contract with a VPP to which it plans to sell energy, then a price forecast for feeding back energy into the grid should be provided for “site level energy management”.

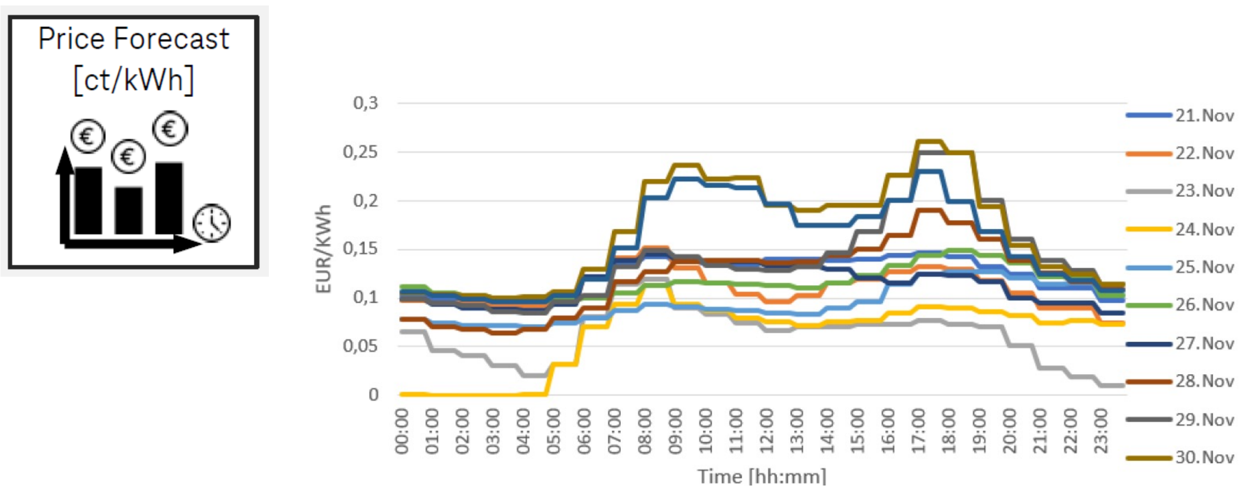


Figure 14. Dynamic tariff partners will provide price forecasts (24h/48h).

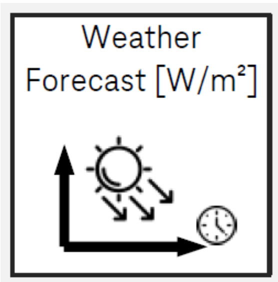
4.2.3 Forecasting Renewable Energy Production

By leveraging weather forecast data, it's possible to make increasingly accurate forecasts of solar and wind energy production, contributing to more efficient integration of renewable power into the energy management system (see Figure 15).

A growing number of public institutions provide simplified models for specific climate regions and technical implementations considering such parameters as azimuth, tilt, type of photovoltaic (PV)-panels, in order to predict the outcome of photovoltaic and wind energy production.

Therefore, the development of energy production models and their implementation is mainly steered by detailed knowledge of asset and configuration data of the renewable energy production system, the availability of sufficiently accurate weather parameters and location data. The sort of weather parameters needed depends on the prediction model for the renewable power and the site-specific implementation of the renewable energy production unit (e.g., height of wind generator determines wind speed at specific heights). The results can be improved by AI-based learning models which consider local effects, not considered by the models (e.g., shadowing by objects like trees, buildings, etc.).

Specific geographical conditions with very low seasonal and daily variations may enhance the accuracy of models based on climatic input data, which in turn may be combined with AI models that consider local effects like shadowing.



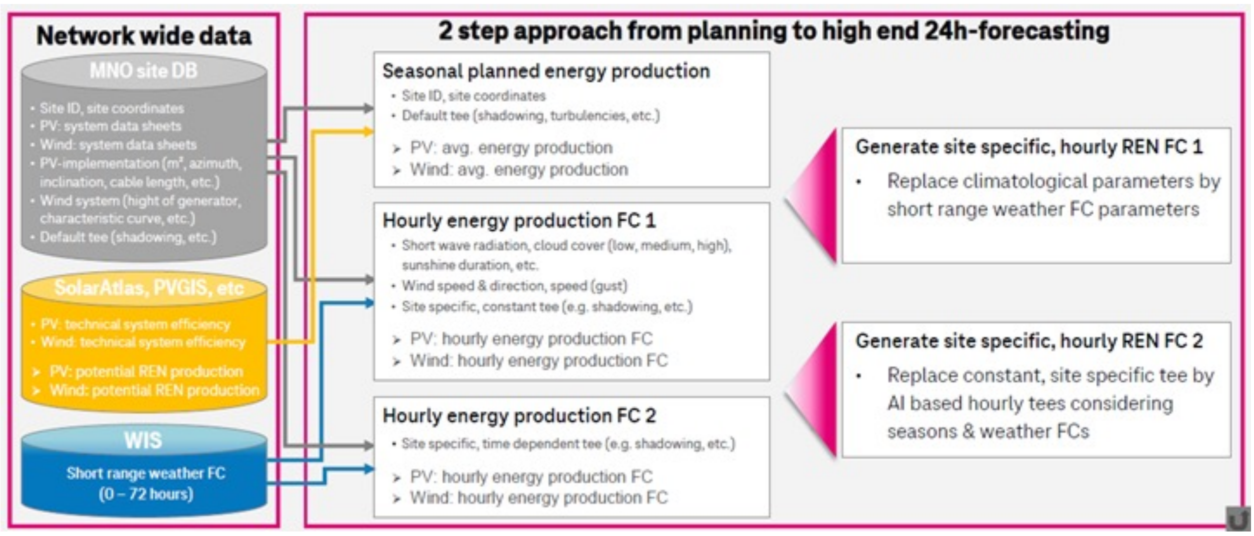


Figure 15. Forecasted meteo-data replace statistical meteorological planning parameters.

4.3 CONSIDERATIONS ON BATTERIES IN ENERGY MANAGEMENT

The peak tariff offered by energy distribution companies to their customers provides an important opportunity for operators to control energy costs and save money. Base stations can reduce unit energy costs to the optimum level by exploiting alternative energy sources or batteries when the tariff is expensive, or from the grid when it is cheap.

It is essential to recognise that the use of batteries in this manner comes with certain drawbacks that can significantly affect the overall system's efficiency and environmental footprint.

A fundamental challenge of using batteries for energy storage and tariff optimisation lies in the power losses associated with both the charging and discharging processes. These losses primarily occur due to the inherent inefficiencies of the AC/DC and DC/AC conversion. Each time the battery is charged or discharged, a portion of the energy is lost in the form of heat, which can decrease the overall energy efficiency of the system. This process is not only costly in terms of lost energy, but it also has an adverse effect on the system's carbon footprint. Increased power losses directly contribute to higher CO2 emissions, especially if the grid's energy mix relies on fossil fuels.

Another consideration is the effect of battery usage on the backup time available in case of a power outage or other emergency. When batteries are used during peak tariff periods, they discharge their stored energy, which reduces the amount of backup power available for critical needs. This, in turn, affects the overall reliability of the energy system, particularly in scenarios where base station availability is crucial. In such cases, optimising for tariff savings by drawing from battery storage may reduce the system's ability to handle unforeseen power interruptions, which could lead to greater vulnerabilities in operational continuity.

The decision to utilise batteries based on fluctuating tariff prices requires a delicate balance between cost savings and system reliability. While using stored energy during high-tariff periods may reduce immediate operational costs, it is important to account for the long-term impacts of power losses, the environmental effects of increased CO2 emissions, and the reduction in backup capacity. Accurate and sophisticated calculations must be made to ensure that the benefits of tariff optimisation do not come at the expense of system resilience or sustainability.

In conclusion, while batteries offer a promising solution for reducing operational expenses, their usage must be carefully considered in the context of both energy efficiency and the potential negative impacts on backup availability and CO2 emissions. AI and data-driven approaches are necessary to achieve an optimal balance that aligns financial savings with environmental and operational goals.

4.4 CONSIDERATIONS ON THE ENERGY FLEXIBILITY MARKET

Each type of market or balancing mechanism (see Chapter 3.1.3) has unique features, such as response times, connection requirements, and service durations. Some mechanisms may require immediate responses, while others allow for longer preparation times. Variability in physical connections to the grid also affects how quickly resources can be mobilised.

To provide flexibility services, several key prerequisites must be met. Firstly, technical resources are essential, including energy storage systems, Energy Management Systems (EMS), remote smart meters, and a stable grid connection. Secondly, the regulatory environment must be adequately developed, encompassing the maturity of TSOs, DSOs, aggregators, and wholesale markets. Established bidding platforms and general legal frameworks that support these services are also necessary. Additionally, cooperation and interoperability platforms among providers, such as those presented in Chapter 6.1.1, are crucial for ensuring effective integration and operation.

Participating in the flexibility market requires adherence to various regulations and standards. Stakeholders must comply with obligations related to demand response programs and capacity markets. Depending on the country, different markets and mechanisms may be available [6]. Countries are working on improving and standardising processes to enhance transparency in synchronisation between them. Cooperation and interoperability platforms provide digital solutions for energy balancing across Europe. They connect national TSOs, consolidate activation bids from member states, and assess bid activation based on cross-border capacity. These platforms enhance the integration of flexibility resources, improve coordination among market participants, and boost overall market efficiency.

4.4.1 Participating to the Flexible services through Energy management

For each flexibility service and for the wholesale market, a specific interface to a commercial service provider (wholesale energy provider, aggregator, etc.) has to be implemented following contractually defined business processes as shown in Figure 16. In this publication, this layer is called "Network level energy management". It defines, manages and controls the procurement of energy from the energy flexibility market - including selling.

The day-by-day negotiated service levels (validity periods for peak limitations and battery capacity for frequency stabilisation, etc.) and prices (24h price forecast, etc.) are handed over to the "Site level energy management". Following policies and guidelines from the energy management strategy (see Chapter 3), the role of the "site-level energy management" is, to find every day the most cost-effective solution for each single site by:

- exploiting the available on-site renewable energy production to a maximum;
- steering the battery charging & discharging in a way that enables buying the energy needed when it is cheapest;
- providing energy to aggregators of DR or ancillary services and/or VPPs, when the operator achieves maximum revenue by supporting these services.

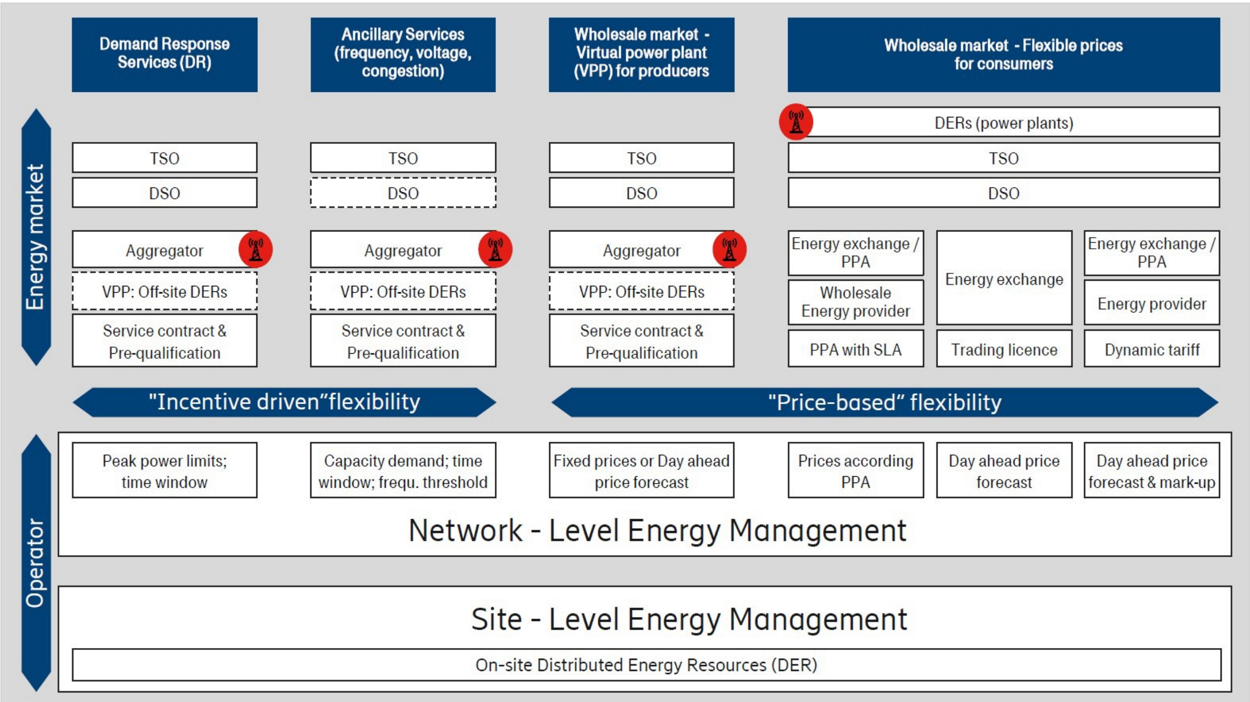


Figure 16. Map of possible MNO participation in the Energy Flexibility Market via Energy Management.

05 SITE-LEVEL ENERGY MANAGEMENT

A Base-Station (BS) site (see Figure 17) is a complex system of electrical consumers, producers and storage systems, handling Alternating Current (AC) and Direct Current (DC). Given the importance of decarbonisation, the variety of energy-related equipment at a BS site has increased as well as the necessity to manage and control the interaction between different bits of such equipment.

According to a statement from Peter Drucker "If you can't measure it, you can't manage it", continuous energy-related measurements of all relevant site equipment (facilities, radio & transmission equipment) is the basis for successful site-level energy management [8].

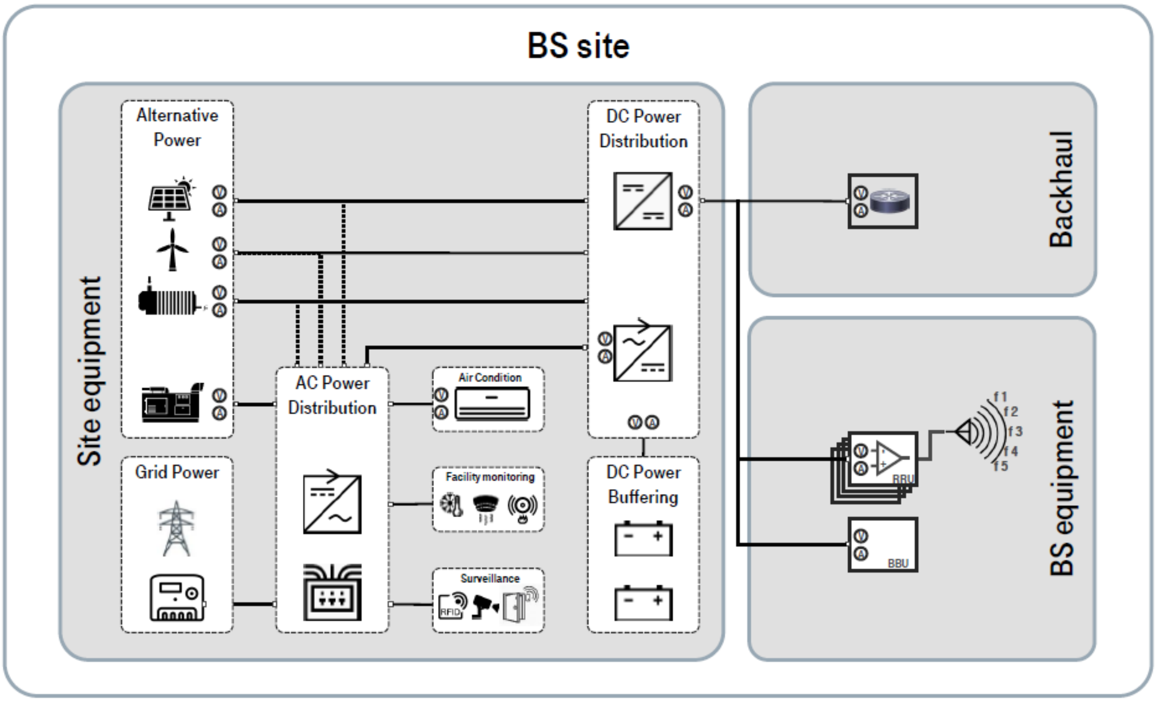


Figure 17. Overview of power sources, power storage & power consumers at a BS site.

As the production costs for renewable energies are decreasing, on-site renewable energy production becomes ever more interesting for MNOs. The management of on-site renewable energy sources in combination with the power grid (multi-source-management, see Chapter 5.1) becomes an important prerequisite.

Renewable energy and the electrification of mobility (e-mobility) are driving progress of cost-efficient batteries. Battery management is key for the storage of excess renewable energy, which will be stored for periods without sufficient on-site production (see Chapter 5.2.3).

But batteries and battery management are also key to leverage the financial benefits from the energy wholesale market and energy flexibility services (see Chapter 5.2.4 and Chapter 5.2.5). This may be a tool to give back control of energy costs to the operators.[5]

5. In this publication the contribution of renewable energy sources and battery storage to site resilience is not considered (This is for further study).

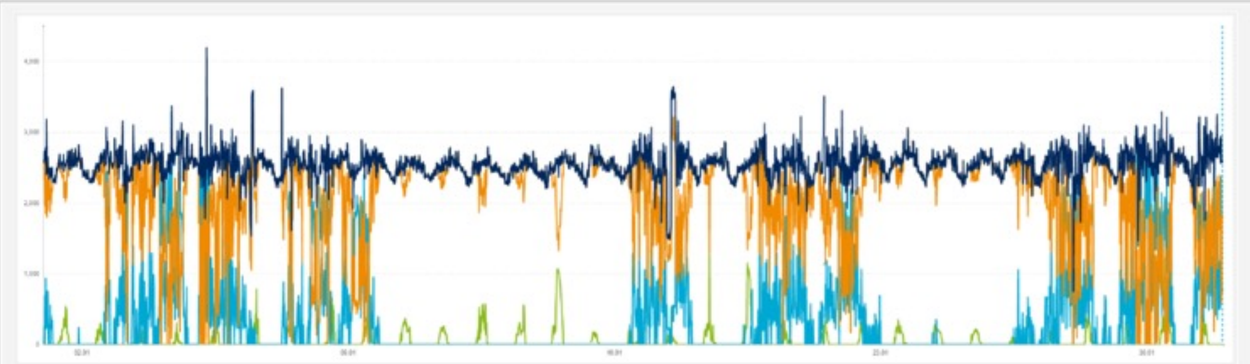
The management of the on-site equipment and reacting to changing energy market conditions are within the domain of site level energy management systems. Today's onsite energy management systems can cope with multi-source management including VRE and changing energy tariffs. The extent to which these functionalities can be simultaneously operated with demand response and ancillary services, depends on the available battery capacity and the operator's specific implementation of energy strategies.

5.1 MULTI-SOURCE ENERGY MANAGEMENT

Over the years a majority of BS sites were operated with a clear focus on the energy management system: AC-grid power must be transformed into DC to supply the radio equipment with DC 48V. In some areas where power outages repeatedly occurred, one of the solutions was, and is, battery deployment. This solution was technically kept as simple as possible, and no remote monitoring and/or control system was needed.

With the implementation of renewable energy production systems (mainly by PV and wind) this is changing. The renewable energies should be the primary source, and they should replace grid energy whenever possible. As the demand for these solutions increased, standardisation bodies took responsibility to provide suitable standards, and suppliers started to develop carrier grade solutions for it. A pilot site was built by an NGMN MNO to test the capabilities of an energy management system, controlling three parallel energy sources provided by the power grid, a PV-system and a wind turbine.

The system with its full FCAPS-capabilities was integrated into the operations environment. Based on the local climatic conditions, wind energy was the top priority followed by PV-energy and grid power. Figure 18 shows the results of this prioritisation: whenever wind energy was available, it was considered the primary source, followed by PV. The remaining energy demand was provided by the grid. This policy could be customised to the requirements of any operator.



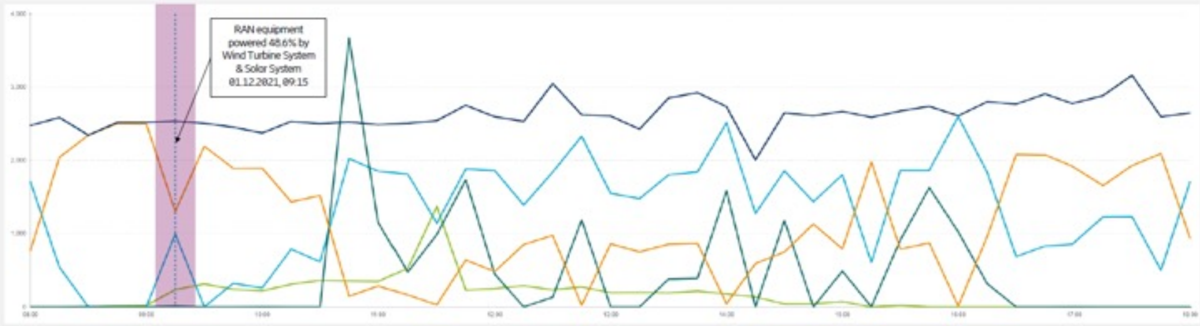
[W]	Minimum	Maximum	Average
E6140 RAN Power*	751 W	4194 W	2550 W
E6140 Grid Power	2 W	3623 W	2134 W
Solar System Power	0 W	1363 W	49 W
Wind System Power	0 W	3285 W	366 W

*Note: "E6140 RAN Power" is defined as measured energy consumption from all RAN equipment (Site Controller, Baseband, Radio & Transmission) connected to Enclosure 6140 (AC input reference).

Figure 18. Grid, solar & wind as sources: control of sources (a typical single month: January).

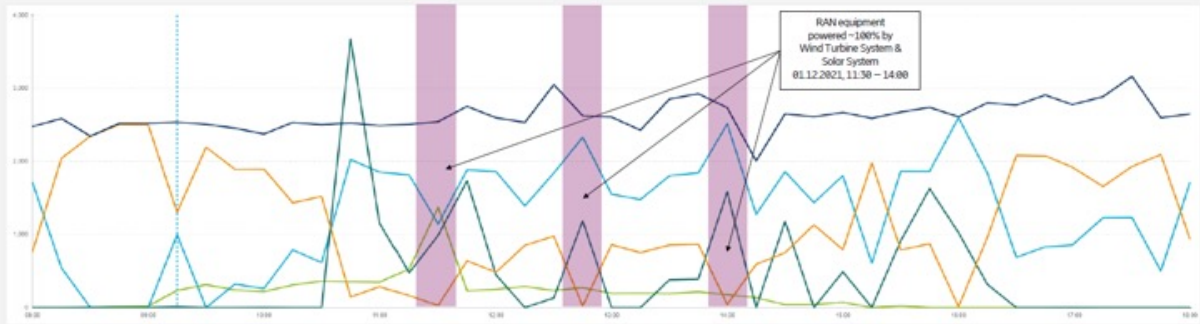
As the weather may change considerably within seconds (clouds shifting in front of the sun, gusts of wind) multi-source energy management systems must react very rapidly to these changing situations. Figure 19 shows the sort of fast switching between various power sources.

Modern energy management equipment is capable of orchestrating several independent energy sources based on customer-specific policies, which can be adopted remotely by configuration management.



System		Actual [W]	Contribution [%]
E6140 RAN Power*	—	2537 W	100.0 %
E6140 Grid Power	—	1305 W	51.4 %
Solar System Power	—	235 W	9.3 %
Wind System Power	—	997 W	39.3 %
Wind Power Load Shedding	—	0 W	N/A

*Note: "E6140 RAN Power" is defined as measured energy consumption from all RAN equipment (Site Controller, Baseband, Radio & Transmission) connected to Enclosure 6140 (AC input reference).



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Wind System Power	—	997 W	39.3 %
Wind Power Load Shedding	—	0 W	N/A

*Note: "E6140 RAN Power" is defined as measured energy consumption from all RAN equipment (Site Controller, Baseband, Radio & Transmission) connected to Enclosure 6140 (AC input reference).

Figure 19. Short term adoption of grid intake as a reaction to availability of energy from renewable sources.

In case the power production by renewable energy sources is higher than the actual demand, the surplus energy can be either fed back into the grid (which demands a specific contract with the energy supplier) or it can be stored in batteries (see Chapter 5.2.3). By effectively managing overproduction from renewable sources, batteries help create a more flexible, resilient, and sustainable energy system. [6]

5.2 ENERGY STORAGE MANAGEMENT

The deployment of batteries together with VRE generation at BS sites should reduce the intake from other main energy sources such as the energy grid or energy generation units (e.g. diesel generators and fuel cells).

Decarbonisation changed the market for electrical energy (see Chapter 2). Today, the grid power is a mix of various nuclear, gas, coal, fuel, renewable (hydro-, solar-, wind-power, etc.) energy production and tariff

6. In this publication, feedback of electrical energy into the public power grid is not considered.

systems with constant pricing (7 x 24 x 365) are dominating the markets. In future, the contribution of renewables to the total mix will increase. Then, due to the fluctuating availability of renewables, flexible prices related to end-customer tariffs, direct trading on the stock exchange or contractual agreements enshrined in PPAs will become increasingly important, and batteries could enable operators to generate arbitrage by using them.

The combination of storing excess energy generated by renewable on-site sources and energy arbitrage (flexible prices) is one of the most promising use cases of on-site energy management. [7]

5.2.1 Limiting Carbon Footprint and Maximising VRE Usage

This chapter presents a site level battery management approach to improve the BS site Network Carbon Intensity Energy (NCIe) index, which measures the network carbon intensity of data transmission.
In the Recommendation ITU-T L.1333 [9], the NCIe is defined as follows:

$$\mathrm{NCIe}\left(\frac{\mathrm{kg\ CO_2}}{\mathrm{TB}}\right) = \frac{CE}{DV},$$

where CE represents total carbon emissions of a site, including carbon emission of the mains and diesel generator, while DV represents the total data volume delivered by the network site.
In addition, the formula for calculating site Carbon Emission Factor (EF) is as follows [9]:

$$\mathrm{EF}\left(\frac{\mathrm{kg\ CO_2}}{\mathrm{kWh}}\right) = \frac{CE}{E_{total}} = \frac{\sum_j E_j \cdot EF_j}{E_{total}},$$

where E_{total} denotes the total consumed electricity consisting of mains power generation, diesel generator power generation and renewable energy power generation, E_j is the consumed electricity related to the jth source of available energy, and EF_j is the emission factor the jth source of available energy. It is important to notice that both NCIe and *EF* consider energy supply chain and distribution losses.

Under determined site energy equipment, the deployment of battery brings the opportunity of reducing carbon emissions, if they are used in combination with energy sources having a low emission factor (e.g., renewable energy sources). As depicted in Figure 20, the key strategy is to discharge the battery before the renewable energy source delivers power, so that any redundant renewable energy that exceeds the site power consumption can be stored by the battery to the extent possible. When the renewable energy is unavailable, the battery can supply energy instead of having to rely on a diesel generator or the mains. How to precisely decide the start and end time instant of charge and discharge process is a crucial problem in battery management to minimise carbon emissions.

7. The discharging of the batteries during high price periods may also be used to feedback energy into the power grid. In this case efficiency losses up to 5% due to inverting DC into AC must be considered.

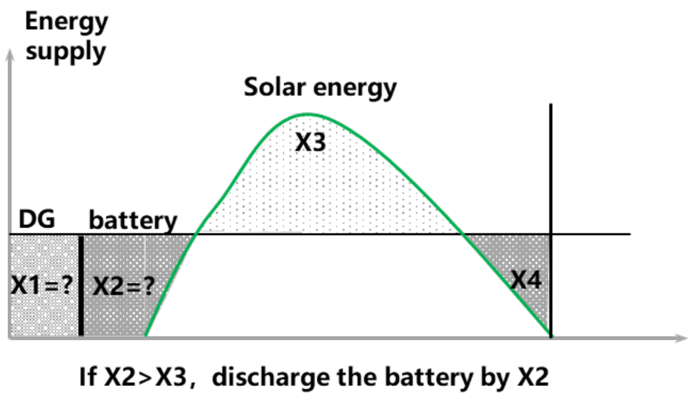

Figure 20. Battery Management Strategy to Reduce the Carbon Footprint.

In the real network, the baseline energy scheduling policy is to select the available energy source with the highest priority (e.g., solar energy > battery > Mains > diesel generator where ">" denotes a higher priority) to supply energy at each time interval. In this chapter, a dynamic programming (DP)-based site level energy management strategy is presented. Firstly, a battery state of charge (SOC) model is established based on the energy storage mechanism. Based on the SOC model, a discrete-time energy decision-making optimisation problem is formulated to minimise carbon footprint by considering carbon emissions and availability of each energy source. Finally, the dynamic programming algorithm is applied to solve the problem, with an optimal energy supply decision obtained at 5-minute intervals.

In order to illustrate the benefits of the proposed energy scheduling strategy, the energy data of 12 sites in Ethiopia, each equipped with a diesel generator, photovoltaic panel and battery, was collected. The Site Energy Efficiency (SEE) [10], Telecom Energy Efficiency (TEE), NCIe and Renewable Energy Ratio (RER) [11] were simulated under the DP-based energy scheduling strategy and the baseline energy scheduling strategy, respectively.

Table 2. Comparison of NCIe and RER under baseline energy scheduling strategy and DP-based energy scheduling strategy

	Energy scheduling strategy	Number of sites	TEE (GB) kWh	SEE	CE (kg CO_2)	EF (kg CO_2) kWh	NCIe (kg CO_2) GB	RER
Redundant solar energy < 3% SOC	**baseline**	9	1.05	60%	82.26	0.43	1.10	34.26%
	DP				77.78	0.42	1.09	35.05%
Redundant solar energy ≥ 3% SOC	**baseline**	3	1.65	60%	51.67	0.36	0.51	38.16%
	DP				39.58	0.32	0.44	41.37

The simulation results shown in Table 2 highlights that, when the solar power generation is significantly larger than the site power consumption, the proposed energy management strategy strongly limits the site carbon footprint while enhancing the site renewable energy usage. In fact, by applying the proposed DP-based energy scheduling strategy, the average NCIe and RER of sites are slightly improved when the solar power generation is similar to power consumption. NCIe notably dropped by 13.73% (from 0.51 to 0.44) and RER improved from 38.16% to 41.37% when the solar power generation was significantly greater than the power consumption.

5.2.2 Battery Supply Coordination

With the rapid growth of distributed renewable energy production, the backup battery resources in the communication equipment room would be expected to support site power adjustment to balance power supply and demand for power grid regulation. Batteries also help to maximise the use of renewable energy. To achieve these goals, communications equipment room batteries store excess renewable energy and discharge at peak power demand. However, batteries used as backup in cases of power outage cannot be so easily integrated into the power grid.

To enable the communications equipment room battery with the capabilities of both energy supply and storage, the battery power supply module must be upgraded. As shown in Figure 21, it currently supports AC 380V/220V conversion to DC 48V. Through battery inverter modification, DC 48V conversion to AC 380V/220V is achieved. Besides, an intelligent control module can be installed on the switching power supply, which acquires real-time battery data and controls battery charging and discharging on demand. For example, it can sense charging and discharging status, number of charging and discharging times, response duration, battery capacity and other indicators.

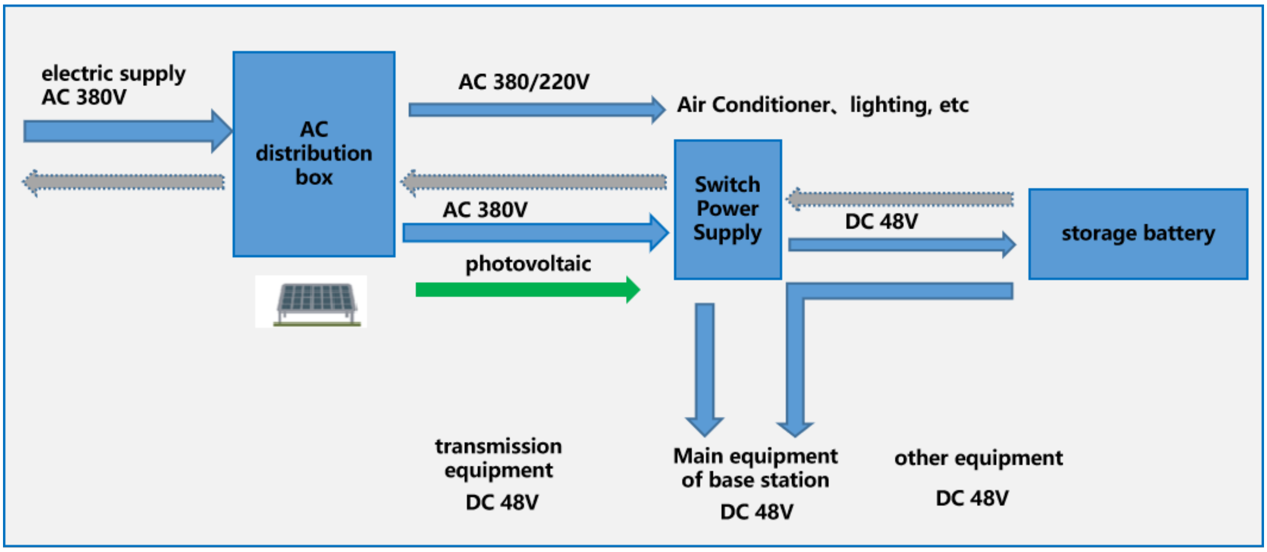

Figure 21.Battery supply and storage synergy.

To reduce the energy cost for base stations, the power consumption mode of base stations needs to be optimised. Firstly, it is vital to monitor the indicators of the power consumption of base stations, renewable energy production and battery storage. By integrating these data with the time-of-use electricity price mechanism, battery charging and discharging instructions can be better regulated and can trigger load mobility among base stations thereby maximising renewable energy utilisation. The key issue in battery backup power is to predict the minimum reserved amount of power for maintaining the availability of base stations, which is related to traffic variations in different periods. In other words, during high-load periods, corresponding to high power consumption of base stations, more power needs to be reserved to cope with potential power grid failures.

To be specific, when the amount of electricity produced by renewable energy exceeds the power consumption of base stations, the intelligent control module should charge the battery. Also, the battery can be charged during the trough of electricity prices. Conversely, the battery implements the discharge strategy when the amount of electricity generated by renewable energy is less than the power consumption of the base stations. In this scenario, base stations should prioritise the supply of renewable energy before the using stored energy from the battery.

5.2.3 Excess VRE Control

Depending on the size of PV panels or wind turbines and the climatic preconditions, the production of renewable energy may be higher than the consumption during specific periods. The grid intake can be (further) reduced, if this excess energy can be stored e.g. in batteries for later use.

A pilot site in Meissen (Saxony-Germany) was built to test the capabilities of an energy management system, controlling excess energy production by a PV-system with batteries. The dimensioning of the PV-panels was chosen in a way, such that the peak power production was significantly higher (up to three times during the sunniest days in summer) than the peak power consumption.

The site is located at 51° north and the PV production is heavily dependent on seasonal changes and the daily weather situation. The yearly power consumption was 17.866 kWh, with 6.178 kWh produced by the PV-system, resulting in a yearly solar ratio of 35%.

During the summer months the solar ratio reached 70%. This could only be achieved as the excess energy of the PV system was stored in batteries. Based on that the grid intake could be reduced by 3.526 kWh (ca. 20% of the yearly consumption).

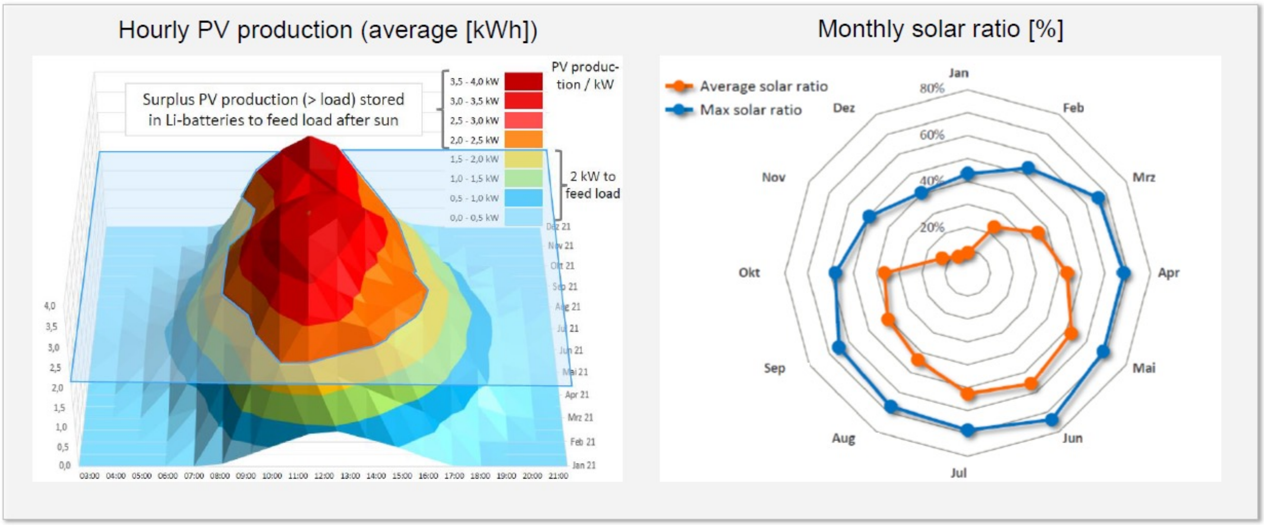

Figure 22. Solar energy production exceeds site power consumption at noon.

5.2.4 VRE Generation and Semi Dynamic Tariffs

In regions where power plants are predominantly producing continuous electrical energy (e.g. based on carriers like uranium, coal, gasoline, natural gas) tariff schemes with fixed peak and low-price windows are offered to motivate customers towards load shifting into these periods. For mobile operators, who cannot influence the customer behaviour and therefore the energy demand, batteries enable energy arbitrage by load shifting, which involves storing energy when prices are low and discharging it when prices are high.

daily weather situation. The yearly power consumption was 17.866 kWh, with 6.178 kWh produced by the PV-system, resulting in a yearly solar ratio of 35%.

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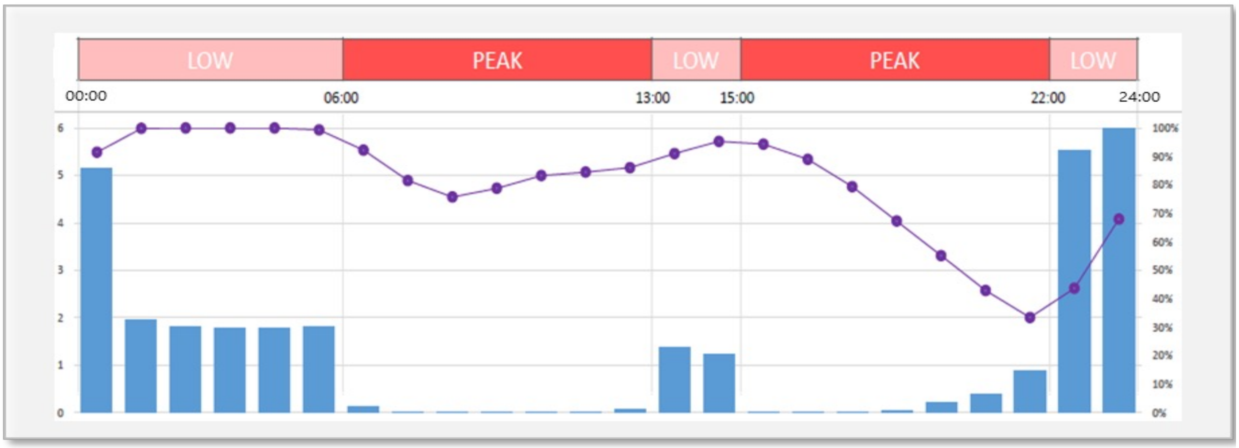

Figure 23. Optimising grid intake windows during low-price windows.

The achievable energy cost reduction depends on:

- the costs for the installed battery capacity and occasionally the renewable energy production system (e.g. PV-system),
- the price difference between peak and low-price windows,
- the duration of the pricing windows

Accordingly, the specific business case would strongly depend on local climatic conditions, tariffs and regulation.

5.2.5 Dynamic Tariffs

Energy markets with a high contribution of renewables to overall energy production face strongly fluctuating prices during a single day (see Figure 24 and Figure 25).

Modern site-level energy management systems use artificial intelligence and real-time data (see Chapter 4.1) to continuously optimise charging & dis-charging cycles of on-site batteries to reduce grid intake during high-price periods. Mature and integrated solutions for mobile operators are expected to be on the market by the end of 2025.

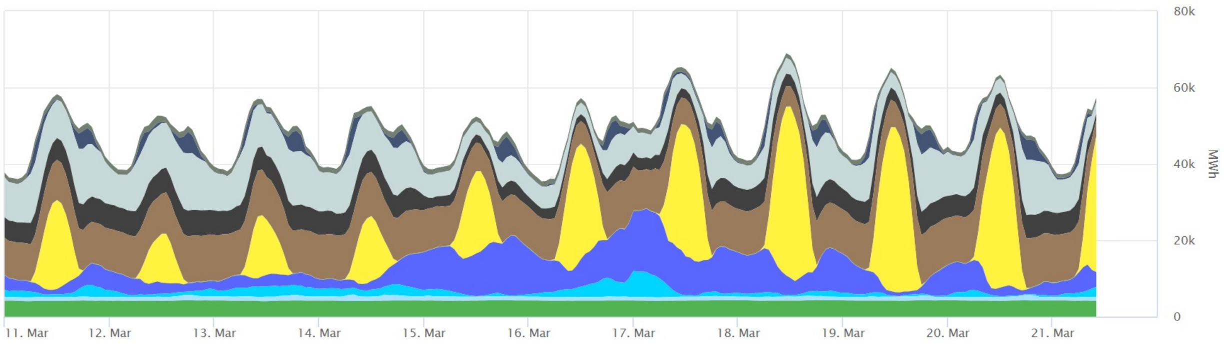

Figure 24. Energy markets with a higher rate of renewable energy production to the total energy production (source: www.smard.de, March 11th -21st, 2025).

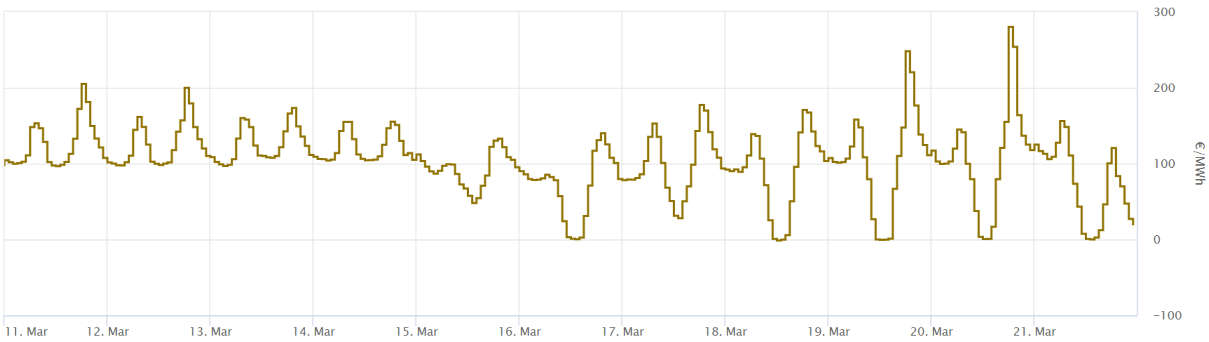

Figure 25. Related day ahead prices (binding 24h price forecasts) on the European energy stock exchange (source: www.smard.de, March 11th -21st, 2025).

06 NETWORK LEVEL ENERGY MANAGEMENT

Participating in the energy flexibility market opens lots of opportunities to mobile operators to reduce energy costs and to even generate new value-added services (see Chapter 3.1.4). As there are many parties involved a complex system of information exchange (see Chapter 3.1.2 and Chapter 4.2) would have to be implemented to connect the participants for making transparent, reliable and secure business transactions. Although the technical challenges of realising flexible energy markets are very similar from one system to another, these systems must fulfil strong national regulatory obligations and are therefore country-specific. The operator-specific energy management strategy (see Chapter 3) defines how an operator participates in the wholesale market and which type of flexibility services will be consumed and to which extent.

6.1 NETWORK LEVEL ENERGY MANAGEMENT AS COOPERATION ARCHITECTURE BETWEEN ENERGY MARKET AND MOBILE NETWORKS

A network-level energy management system must manage all interactions to the northbound market participants (i.e., the green shaded area of the Energy Flexibility Market in Figure 26). It is an integrated part of a MNO's procurement processes – from vendor selection till billing and settlement. At the southbound interface towards the site-level energy management system it provides condensed information about 24h price forecasts, periods of capacity demand and grid intake limitations (see the bottom part of the green shaded area in Figure 26).

A network-level energy management system is the glue between the "market" and the management of on-site DERs in the most cost-efficient manner. It is a highly customised platform with arbitrary complexity, resulting from the number of external APIs, that must be served and the mapping into MNO-specific procurement and risk management processes.

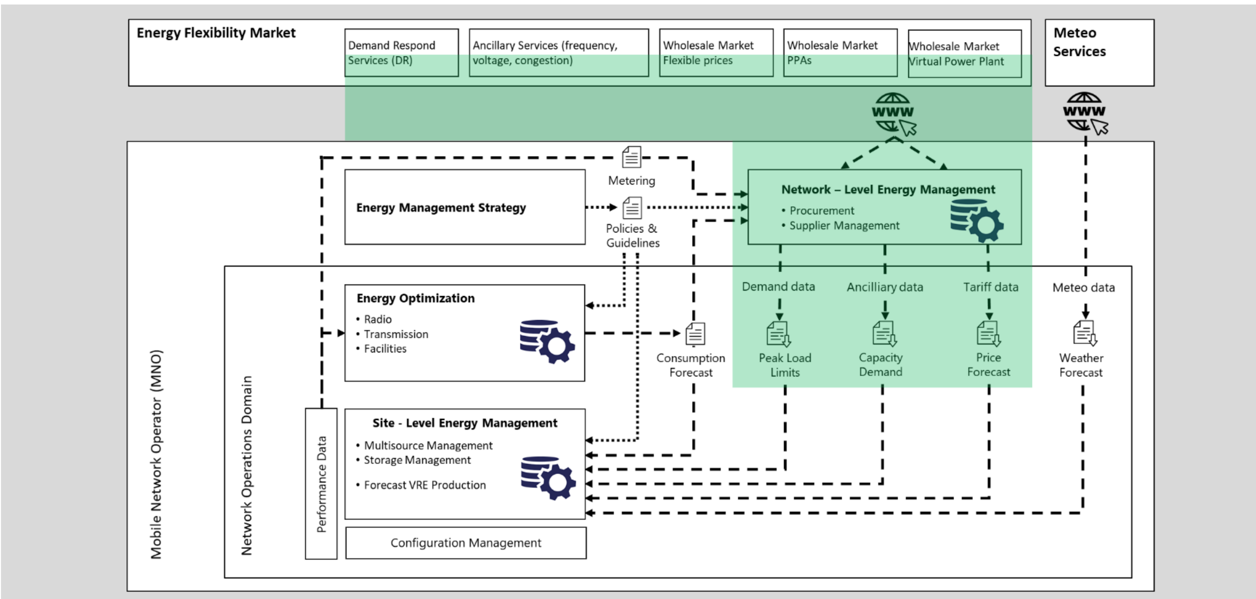

Figure 26. Network-level energy management systems: the green area is the content of this chapter.

6.1.1 Exemplary Solution for Ancillary Services – Europe

The European Union is harmonising the frequency balancing market. It is providing 3 platforms for different balancing products:

- PICASSO (Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation) optimises load balancing through aFRR (automatic Frequency Restoration Reserve).
- IGCC (International Grid Control Cooperation) is the European platform for the imbalance netting process. The system prevents simultaneous activation of aFRR reserves between two TSOs in opposite directions.
- MARI (Manually Activated Reserves Initiative) is developed for the management and optimisation of mFRR (manual Frequency Restoration Reserve).
- TERRE (Trans-European Replacement Reserves Exchange) is the platform for the exchange of balancing energy from replacement reserves (RR). The platform is expected to be decommissioned by the end of 2025. -> Responsibilities shall be integrated into MARI.

Together with the harmonisation of platforms, important characteristics (minimum and maximum quantity, bid granularity, minimum duration of delivery duration, etc.) will be standardised, others remain within the responsibilities of the countries (gate closures, preparation-, ramping-and deactivation period, maximum duration of delivery period, etc.).

If an MNO strategy were to favour ancillary services and to adopt the aggregator's role, the network-level energy management system must serve the above-mentioned APIs and underlying processes. If the strategy were to assume the end-user's role, the contractual obligations must be supported by a proprietary API towards the aggregator.

Responsibilities of the network-level energy management system are (see Figure 27)

I. In case MNO acts as "aggregator":
   - support APIs and processes of platforms towards TSOs;
   - implement an internal platform to communicate with "site-level energy management" to activate reserved capacities on demand

II. In case MNO acts as "end-user"
   - support proprietary APIs and processes towards aggregator
   - implement data flow management to "site-level energy management" to activate reserved capacities on demand

III. Provide interfaces to MNO internal finance tools for billing & settlement

IV. Provide capacity forecast to the "site-level energy management" to enable charging or dis-charging of batteries ready for activation during the given validity period.

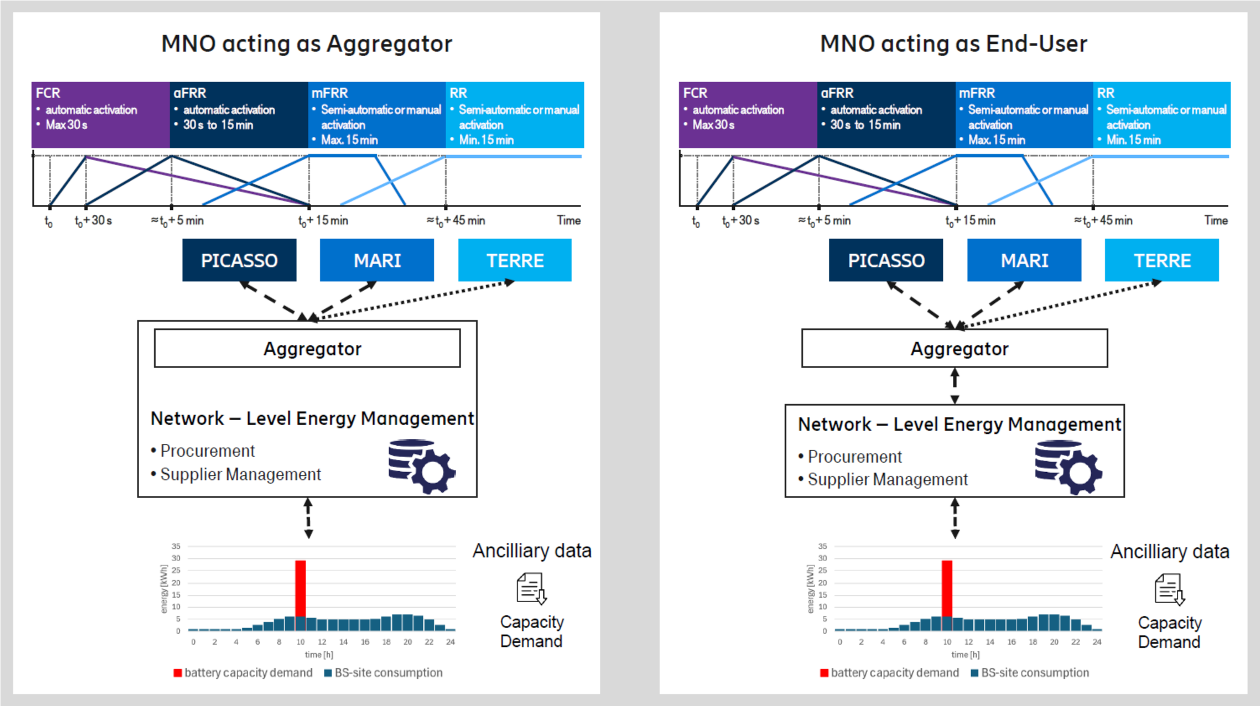

Figure 27. Participating to ancillary services – Europe overview including platforms.

6.1.2 Exemplary Solution for Virtual Power Plants – China

The construction of China's energy market is being steadily and orderly promoted, gradually forming a unified energy market system where various flexibility services coexist, including long-term PPAs, spot markets, auxiliary services and VPPs. MNOs, by virtue of their sizeable, distributed resources (such as site energy and data centers) and digital capabilities, have become important emerging participants in China's energy market (see Figure 28). Among them, VPPs are one of the main ways for Chinese MNOs to participate in the energy market currently.

Participation in the virtual power plant requires that the power supply and batteries possess rapid response capabilities. By aggregating adjustable loads such as energy storage batteries into a load-type VPP, a distributed VPP cluster can be formed to interface with interactive platforms of the power grid, enabling participation in market peak regulation and demand response. During the response period, coordinated dispatching is conducted to achieve targeted reductions in power output, while real-time monitoring and forecasting of load fluctuations are carried out. To ensure communication quality and energy supply security, the grid-side responsive load can be effectively and fully utilised. The following stakeholders would have the corresponding responsibilities respectively.

- MNOs: Connect batteries and other infrastructure to the virtual power plant platform as dispatchable flexible resources, and update data such as battery State of Charge (SOC) and load demand to the VPP management platform.
- Energy Management Contracting Company (Aggregator): Develop the VPP management platform to aggregate resources from MNOs, optimise charging and discharging strategies, and maximise participation in market peak shaving and demand response.
- Grid Operator (TSO): Formulate market rules and conduct transaction management, respond to real-time dispatch instructions to coordinate the collaborative operation of virtual power plants and the electricity network.

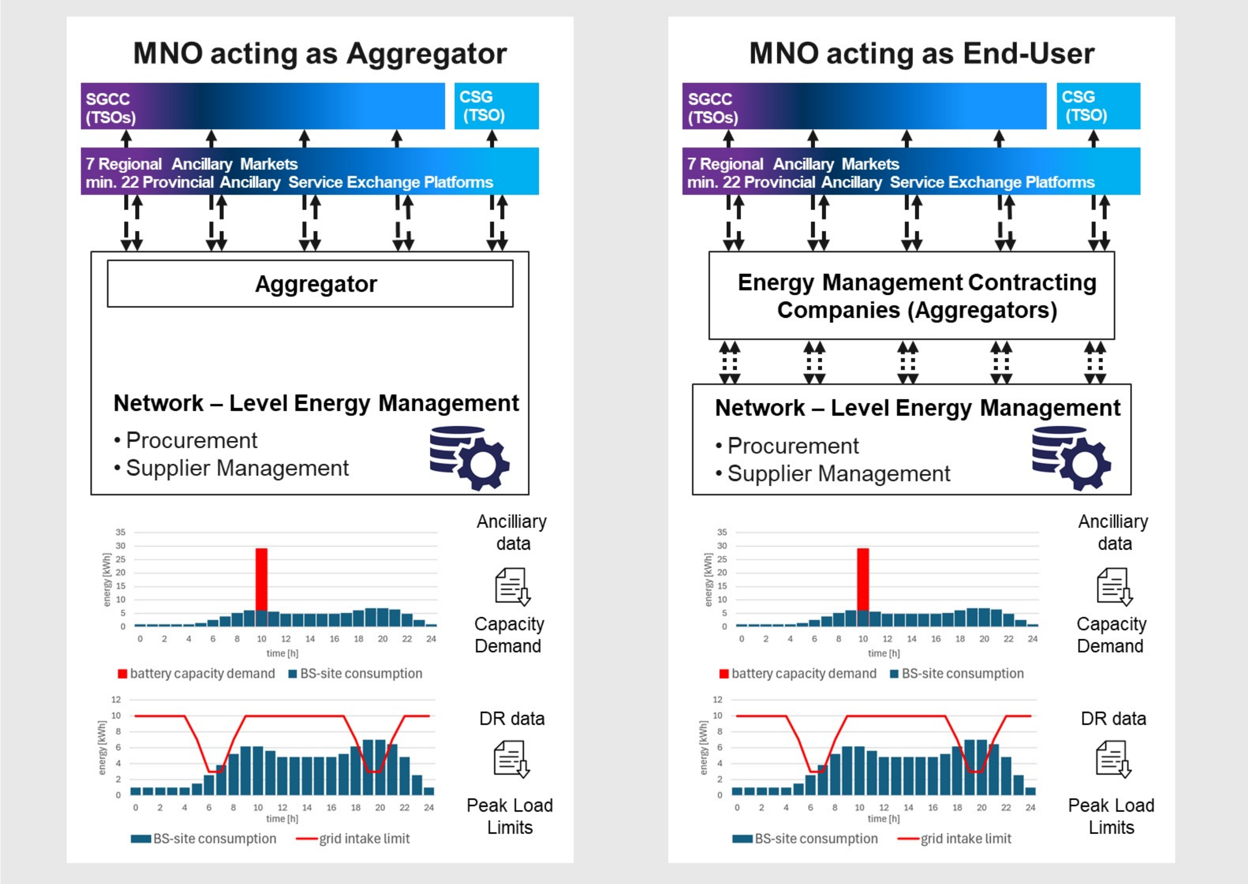

Figure 28. Participating to ancillary services – China overview including platforms.

The Chinese Energy Market for ancillary services is built in 3 stages (initial stage 2020-2025; development stage 2025-2030 followed by mutual stage). Currently, demand response (DR) is mainly involved in peak shaving ancillary services.

The market of DR services is based on provincial regulations, which were laid out from the end of 2021 and completed in 2023. From the perspective of pricing mechanisms, each province has set different price ranges or compensation levels for various DR programs to fully incentivise various types of users to participate in demand response.

6.1.3 Exemplary Solution for DR Services – North America

While the regulations for the European market of DR services is under development, the DR services are already widely implemented in the North American market.

A regional transmission organisation (RTO) in the United States is an electric power TSO that operates a region's electricity grid, administers the region's wholesale electricity markets, and provides reliability planning for the region's bulk electricity system. An independent system organisation (ISO) is similar to an RTO but with less responsibility for the transmission network. All responsibilities are regulated by the Federal Energy Regulatory Commission (FERC).

The DR programs pay qualifying participants to reduce their consumption for discrete periods of time.

As of 2023, there were ten ISOs/RTOs operating in North America. Therefore, a US nationwide MNO may deal with up to 10 ISOs/RTOs. They are providing proprietary APIs to support ancillary and DR services as well as to operate regional wholesale markets. This leads to complex interface handling for multi-state-DR-service-participants. To overcome this complexity, multi-ISO/RTO aggregators entered the market, offering one single interface to cover DR services for several ISOs/RTOs (see Figure 29).

Responsibilities of the network-level energy management system are:

I. In case MNO acts as "aggregator":

- support APIs and processes of platforms towards ISOs/RTOs;
- implement internal platform to communicate with "site-level energy management" to provide grid intake limitations.

II. In case MNO acts as "end-user"

- support proprietary APIs and processes towards aggregator
- implement data flow management to "site-level energy management" to provide grid intake limitations.

III. Provide interfaces to MNO internal finance tools for billing & settlement

IV. Provide forecast of peak load limits to the "site-level energy management" to enable charging or dis-charging of batteries within the given power limits during the given validity period (see Figure 26: "DR data - Peak Load Limits").

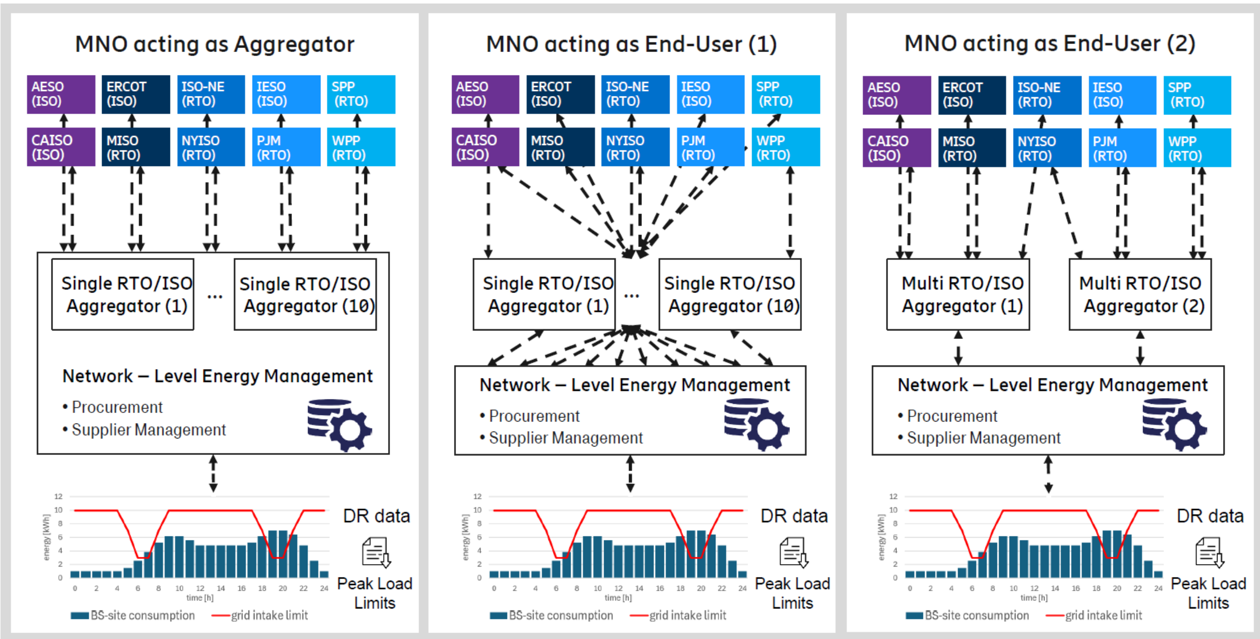

Figure 29. Participating to DR services – North America overview: three possible implementations with exemplary data flows.

6.1.4 Exemplary Solution for Wholesale Markets – Europe

The small-scale segmentation of European countries was an incubator for early cross-border energy trading. The European Community strongly focused on the liberalisation of the energy market and non-discriminating access of green energy producers, resulting in a highly competitive national and international wholesale marketplaces including spot exchange marketplaces.

The European energy market is undergoing a significant transformation with the planned implementation of a 15-minute Market Time Unit (MTU) in the Single Day-Ahead Coupling (SDAC) by June 2025. This initiative aims to enhance market efficiency, better integrate renewable energy sources and improve grid stability across Europe.

Every European exchange market is defining technical, legal and commercial (e.g. liquidity reserves, etc.) prerequisites before registration and before granting access to the marketplace via proprietary trading APIs.

As opening and closing of orderbooks of day-ahead and intraday auctions might differ between various marketplaces, price optimisations can be achieved by staggered auctioning. This leads to a complex interface handling for multi-marketplace participants (see Figure 30). Specific energy providers, offering dynamic tariffs, may take over this role as a broker for MNOs, requesting contractually agreed mark-ups over the day-ahead prices.

Responsibilities of the network-level energy management system are (see Figure 30)

I. In case MNO acts as "licensed trader" on the spot exchange:
   a. support APIs and processes of platforms towards exchange markets.
   b. implement internal platform to communicate with "site-level energy management" providing areal and/or network wide 24h price forecasts.

II. In case MNO acts as "end-user"
   a. support proprietary APIs and processes towards "energy provider/broker"
   b. implement data flow management towards "site-level energy management" to communicate areal and/or network wide 24h price forecasts.

III. Provide interfaces to MNO internal finance tools for billing & settlement

IV. Provide 24h price forecasts (see Figure 26: "Tariff data – Price Forecast").

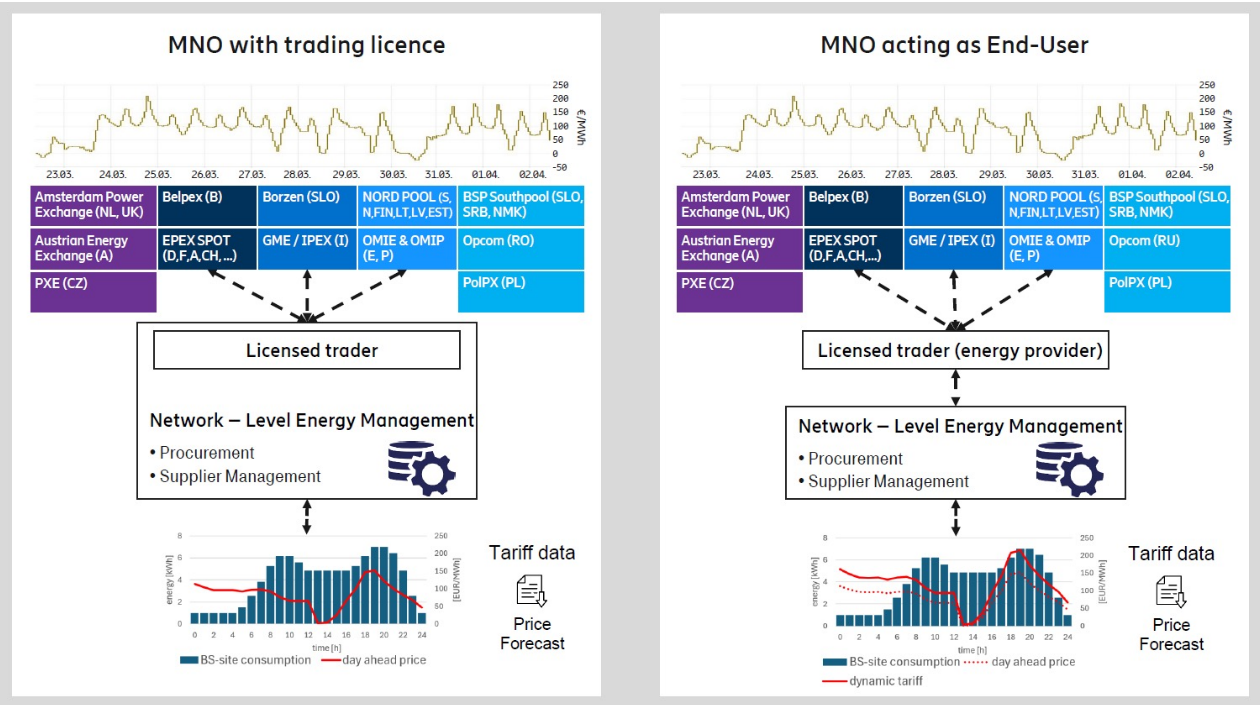

Figure 30. Participating to wholesale markets with day-ahead prices – overview Europe: three possible implementations with exemplary data flows

6.2 COORDINATING NETWORK ENERGY MANAGEMENT AND NETWORK PERFORMANCE MANAGEMENT

The classic energy-saving solution aims to migrate traffic towards the most energy-efficient sites to minimise power consumption of the wireless network by optimising network parameters. This creates the following challenges:

- The network availability rate cannot be guaranteed when the energy-efficient sites are short of reliable energy supply
- NCIe of the network will be high if the energy-efficient sites are powered by diesel generators and lack equipment to supply renewable energy.

In order to reduce carbon emissions without affecting the network availability rate, a collaboration strategy between energy supply and power consumption is introduced, aiming to migrate traffic towards sites with renewable energy and sufficient energy supply. The strategy consists of three key steps, as is depicted in Figure 31:

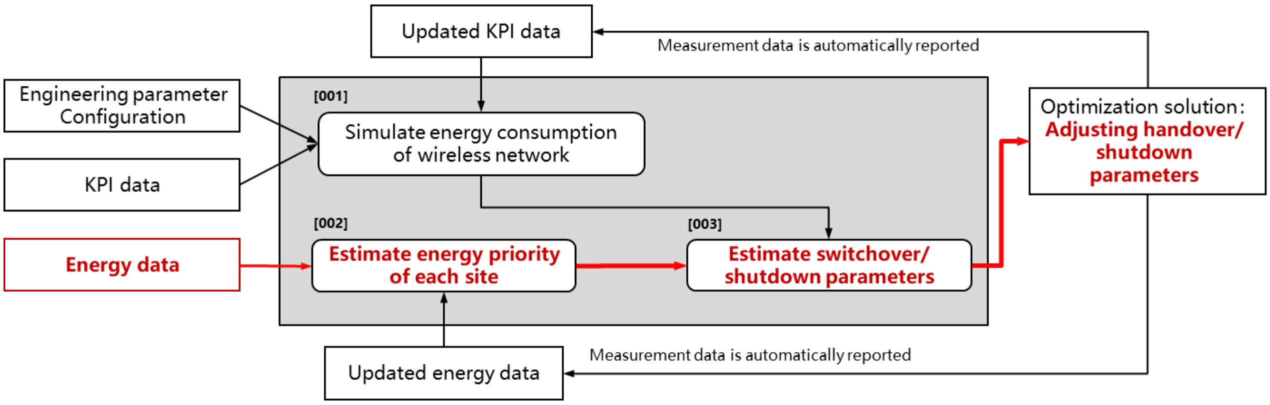

Figure 31. The framework of the collaboration strategy between energy supply and power consumption

Step 1. Establish the energy consumption prediction model by engineering parameter, configuration and Key Performance Indicator data of the wireless network.

Step 2. Estimate the energy priority of each site based on the historical energy data. Sites with high energy availability rate and low carbon emission will have high energy priority.

Step 3. Adjust the shutdown and handover parameters to shut down the sites with lowest energy priority and migrate traffic towards sites with high priority.

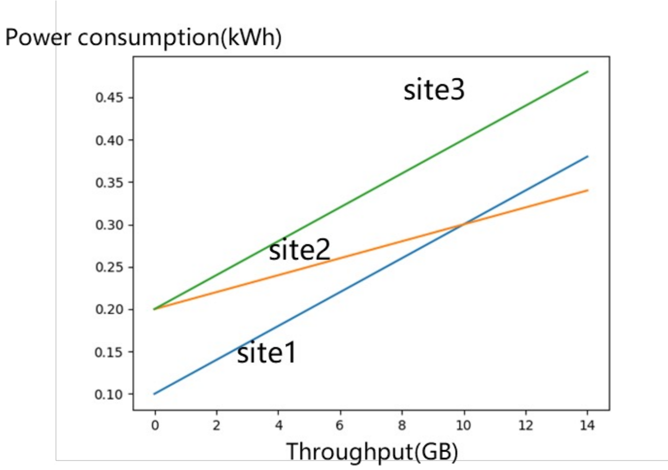

Figure 32. Energy efficiency curve of each site

A simulation was conducted on 3 sites for 24 hours to illustrate the benefits of the collaboration strategy. The energy efficiency curve of each site is shown in Figure 32, and the available energy source of each site is presented in Table 3. The simulation results are exhibited in Table 4, where strategy1 and strategy2 represent the classic energy-saving strategy and the collaboration strategy between energy supply and power consumption, respectively.

Table 3. Available energy source of each site

	Mains	Solar energy	Battery
Site 1	✓	X	✓
Site 2	✓	X	✓
Site 3	✓	✓	✓

Table 4. The distribution of throughput and total carbon emission of 24 hours

	Troughput (GB)		MAins(kWh)		Solar energy (kWh)		Carbon emission (kg CO2)	
	Strategy 1	Strategy 2	Strategy 1	Strategy 2	Strategy 1	Strategy 2	Strategy 1	Strategy 2
Site 1	215.00	135.83	8.00	0	0	0	3.12	0
Site 2	240.00	169.17	11.00	7.65	0	0	4.29	2.98
Site 3	90.00	240.00	0	0	33.60	51.00	0	0
Total	545.00	545.00	19.00	7.65	33.60	51.00	7.41	2.98

By implementing the classic energy-saving strategy, most of the throughput is migrated to site1 and site2 with high energy efficiency, but without a renewable energy source, leading to high carbon emissions. By applying the collaboration strategy, the network traffic is redistributed according to the power supply capability and carbon emission intensity of sites. Since the usage of the mains power is reduced and the renewable energy usage efficiency is improved, the carbon emission reduction is significantly improved from 7.41kgCO_2 to 2.98kgCO_2.

6.3. EFFICIENT ENERGY CONSUMPTION INFORMATION EXCHANGE ACROSS NETWORK NODES

The exchange of energy consumption information between base stations can help a base station understand the energy consumption status of neighbouring base stations. When a base station adopts energy-saving strategies (e.g., cell activation/deactivation), it not only needs to consider how much energy consumption is reduced for itself but also needs to consider the overall energy increase or decrease across all base stations in the area caused by its energy-saving strategy.

Therefore, when introducing AI/ML for energy consumption prediction, a base station can collect the actual energy consumption data of neighbouring base stations. Based on the current energy consumption of neighbouring base stations and its own planned energy-saving strategy, the base station can predict the increase in energy consumption of neighbouring base stations and the decrease in its own energy consumption. This allows the base station to assess whether the energy-saving strategy is beneficial or detrimental.

To effectively reflect the energy consumption of the network, one approach is to configure a unified mapping rule between Energy Consumption (Unit: J) and Energy Cost (an index between 0 and 10000) among multiple Next Generation Node Bs (gNBs) within a defined area. The gNBs know their minimum and maximum energy consumption values, and the value 0 of the Energy Cost index is associated to a single energy consumption value, configured based on the minimum energy consumption of the gNBs in the defined area, and the value 10,000 of the Energy Cost index is associated to a single energy consumption value, configured based on the maximum energy consumption of the gNBs in the same area.

The example is provided in Figure 33 to explain how the mapping rule is applied.

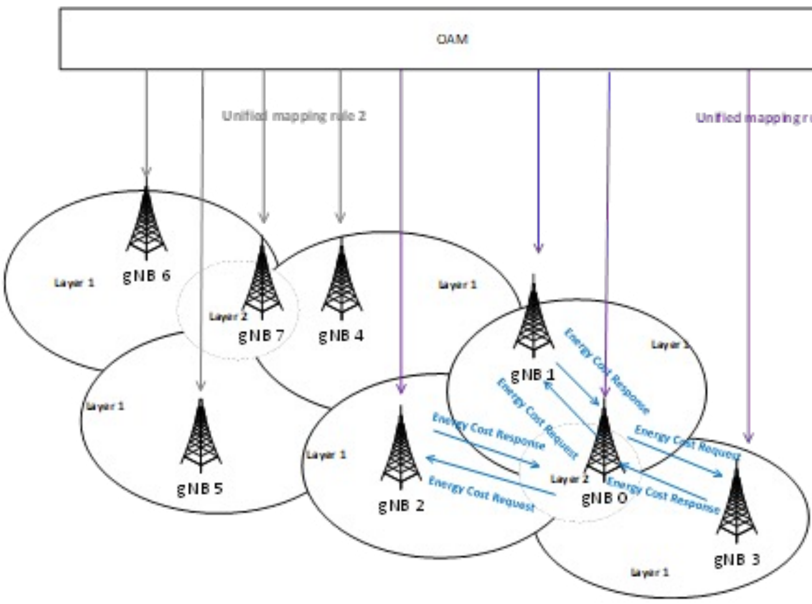

Figure 33. Example of Energy Cost exchange between gNBs.

In this scenario, gNB0 manages cells for capacity and considers offloading traffic to neighbouring gNBs (gNB1, gNB2, and gNB3) to switch off its own cells for energy savings. To make an optimal AI/ML-based energy-saving decision, gNB0 requires Energy Cost value from its neighbours, calculated similarly to its own. This ensures a fair comparison of energy consumption before and after offloading within the defined area.

07 BEST PRACTICES

Energy management is a key topic for the mobile industry to address in order to meet both environmental goals and to manage costs. The identified energy management strategies will require different levels of investment for MNOs to realise cost reduction, reliability and sustainability benefits, as well as opportunities to generate new revenue. Beyond direct benefits to operators, adoption of some of the energy management strategies will support the evolution of the VRE phase in the country where the MNO operates by increasing the percentage of renewables in the grid energy mix.

Table 5 summarises the high-level benefits of the identified energy management strategies.

Benefit	Grid First	Site level	Network level
Required operator Investment	Low*	Medium	High
Support expansion of Grid renewable capacity			✓
Can reduce need for grid upgrade		✓	✓
Maximise use of low carbon energy from grid	✓		
Reduce operator reliance on peak tariff energy		✓	✓
Ability to reduce pressure on grid to support network peak energy demands		Medium	High
Create opportunity for additional operator revenue			✓
Maximise use of operator own generated VRE		✓	✓

Table 5. High level benefits of the energy management strategies discussed in this white publication.

The NGMN Alliance makes the following recommendations with a view to advancing this important area of work within the industry and with industry partners.

Planning for the integration of Variable Renewable Energy

1. Operators should consider the VRE integration phase in their country when selecting energy management strategies.
2. Strategies where operators rely heavily on the grid to meet their demand for low carbon energy only make sense in countries which are at a more advanced phase of integrating VRE into the grid.
3. Operators must think carefully before investing heavily in their own VRE generation in countries which are already at an advanced stage of VRE integration into the grid.

Energy Management at the site-level

1. Energy Management on a per site level basis must consider the energy sources available (e.g. 'clean' grid energy, local renewable energy, battery), traffic load, and availability and cost of each energy source over time.
2. Operators will need to determine suitable energy management strategies in line with their strategic goals: for example, minimisation of energy costs and/or minimisation of carbon emissions.
3. Energy Management must consider regulatory requirements related to mobile service continuity in the event of power outages.

Role of Network Management and AI

1. Network Management and automation powered by AI will have a key role to play in energy management for MNOs.
2. MNOs must ensure any data ingested from 3rd parties (e.g., weather and energy cost) is verified and trustworthy with procedures in place to rapidly recover from faulty data.
3. Due to the critical nature of mobile networks – whereby they are often designated as of national importance – MNOs must be aware of and be able to demonstrate to regulators that any AI developed and deployed to manage energy will do so within acceptable limits for network availability and network performance. The industry should study how such transparency can be (independently) verified.

Energy Flexibility and the role of MNOs

1. Energy management systems shall be capable of rapid reaction to external triggers not initiated by the element management system but from an external source.
2. On-site energy management systems (e.g. site controller) must fulfil regulatory requirements for the energy flexibility market.
3. Demand response service providers must comply with evolving national legislation, while MNOs' internal security guidelines must be fulfilled by their service providers.
4. To maximise the potential for Variable Renewable Energy the mobile industry should work with the energy industry to achieve a suitable standardisation and regulatory environment that encourages harmonisation.

08 LIST OF ABBREVIATIONS

Abbreviation	Description
AC	Alternating Current
ACER	Agency for the Cooperation of Energy Regulators
aFRR	automatic Frequency Restoration Reserve
AESO	Alberta Electric System Operator
AI	Artificial Intelligence
CAISO	California Independent System Operator
CAPIF	Common API Framework
DC	Direct Current
DER	Distributed Energy Resources
DP	Dynamic Programming
DR	Demand Response
DSM	Demand Side Management
DSO	Distribution System Operators
EDRP	Emergency Demand Response Program
EF	Emission Factor
EMS	Energy Management System
ERCOT	Electric Reliability Council of Texas
FCAPS	Fault Configuration Accounting Performance and Security
FERC	Federal Energy Regulatory Commission
FRC	Frequency Containment Reserve
gNB	Next Generation Node B
IEA	International Energy Agency
IESO	Ontario Independent Electricity System Operator
IP	Internet Protocol

ISO	Independent System Organisation
ISO-NE	ISO New England
mFRR	manual Frequency Restoration Reserve
MISO	Midcontinent Independent System Operator, Inc.
ML	Machine Learning
MNO	Mobile Network Operator
MTU	Market Time Unit
NCIe	Network Carbon Intensity Energy
NYISO	New York Independent System Operator
PJM	PJM Interconnection
PPA	Power Purchase Agreement
PV	Photo Voltaic
RER	Renewable Energy Ratio
RES	Renewable Energy Sources
RR	Replacement Reserves
RTO	Regional Transmission Organisation
SCR	Special Case Resource
SDAC	Single Day-Ahead Coupling
SEE	Site Energy Efficiency
SGU	Significant Grid Users
SOC	State of Charge
SPP	Southwest Power Pool
TEE	Telecom Energy Efficiency
TSO	Transmission System Operators
VRE	Variable Renewable Energy
VPP	Virtual Power Plant
WPP	Western Power Pool

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NEXT GENERATION MOBILE NETWORKS ALLIANCE

NGMN – the Next Generation Mobile Networks Alliance – is a global, operator-driven organisation, established by leading international mobile network operators (MNOs). As a global alliance of nearly 70 companies and organisations – including operators, vendors, and academia – NGMN provides industry guidance to enable innovative, sustainable and affordable next-generation mobile network infrastructure.

NGMN drives global alignment of technology standards, fosters collaboration with industry organisations and ensures efficient, project-driven processes to address the evolving demands of the telecommunications ecosystem.

VISION

The vision of NGMN is to provide impactful industry guidance to achieve innovative, sustainable and affordable mobile telecommunication services to meet the requirements of operators and address the demands and expectations of end users. Key focus areas include Mastering the Route to Disaggregation, Green Future Networks and 6G, while supporting the full implementation of 5G.

MISSION

The mission of NGMN is:

- To evaluate and drive technology evolution towards the three **Strategic Focus Topics:**
  - **Mastering to the Route to Disaggregation**
    Leading in the development of open, disaggregated, virtualised and cloud native solutions
  - **Green Future Networks**
    Developing sustainable and environmentally conscious solutions
  - **6G**
    Providing guidance and key requirements for design considerations and network architecture evolution
- To define precise functional and non-functional requirements for the next generation of mobile networks
- To provide guidance to equipment developers, standardisation bodies, and collaborative partners, leading to the implementation of a cost-effective network evolution
- To serve as a platform for information exchange within the industry, addressing urgent concerns, sharing experiences, and learning from technological challenges
- To identify and eliminate obstacles hindering the successful implementation of appealing mobile services.