THE UNIVERSITY OF SYDNEY

# Digital Energy Systems

## Challenges, opportunities and technologies

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# 1. Executive summary

**Australia is at the forefront of the uptake of distributed energy resources (DER) globally. According to the Australian Energy Market Operator (AEMO), power supply will consist mostly of renewable energy sources by 2040, with more than 20% coming from small-scale DER.**

**The objective of this white paper is to provide a better understanding of the current digital energy systems landscape as reviewed by leading University of Sydney researchers, industry and business partners including The Warren Centre and Nokia. It assesses the current situation and looks toward the future to identify where and what sort of challenges are likely to arise. It aims is to trigger further collaboration between the research community, industry and government agencies, as Australia seeks to find an effective, integrated solution to the nation's distributed energy resources.**

## Challenges

The challenge is to harness this intermittent energy. Today home solar owners in Australia are paid about 10 cents/kWh for electricity they export to the grid, but the retailers sell it for 30+ cents. There are two huge opportunities. Firstly, there is the commercial opportunity. The financial gap is huge. Can we manage this exported solar and distribute it to local customers? Who will manage it? What is needed to make this new exchange of electricity work and create a new 2-way market?
Secondly, rooftop solar generates power on demand side of the power meter. The emerging issue is low demand associated with overvoltages and reverse power flows, not peak demand as in conventional grids. However, if these sources of power are controlled, they can actually balance the network.

Network companies can only manage the rapid uptake of rooftop solar by curtailing existing rooftop solar generation and preventing new connection, which is against the interest of prosumers.

The current demand response practices, that use flexible loads can shift demand by a few hours to reduce peak demand. However, these shift practices often do not consider the end users' comfort requirements. Regardless, an increasing number of new rooftop solar installations come with battery storage. Battery storage, coupled with an intelligent energy management system (EMS), can effectively decouple energy and power consumptions, which preserves prosumer prerogative and privacy by allowing them to manage their own energy.

Using demand response for system operation is now possible at a new level. However, achieving the full potential requires aggregating DER into virtual power plants (VPPs). The existing VPPs that directly control individual batteries to achieve demand response allow the VPP operator to improve its position in the wholesale market.

## Opportunities

To enable a proper two-sided market where VPPs both trade in the wholesale market and offer network support services, the DER aggregation problem needs to be formulated as an optimisation problem, akin to economic dispatch used in the wholesale market. To solve the problem and address privacy issues, a distributed approach is needed.

The distributed aggregation approach distributes the computation burden among prosumers agents where prosumers solve their own energy management problem and iteratively exchange messages with the aggregator until convergence. While this approach is feasible computationally, it does require a communication network with sufficient latency, reliability and bandwidth.

## A framework

Changes are also required in the regulatory framework to support a future two-way market. Network companies do not have a contractual relationship with customers to manage their dispatchable solar electricity. If they were to use prosumer-owned DER for-network support, the regulatory framework would need to shift from the current regulated cost-plus-compensation model towards a model that encourages the provision of new products and services. To realise these opportunities, network companies will need to work together with DER aggregators and retailers to facilitate distribution energy markets with full prosumer participation. The newly developed market platforms will enable the monetisation of new products and services across the value chain.

## Our expertise

The University of Sydney's Faculty of Engineering is uniquely positioned to address the challenges of Digital Energy System integration. The School of Electrical and Information Engineering has world leading expertise in power systems, power electronics, the Internet of Things (IoT), telecommunications, optimisation and artificial intelligence (AI). Our multiple disciplinary team has a history of successful industry collaboration, including the Smart Grid Smart City project and the award-winning ARENA project CONSORT. We have partnered with Nokia to develop solutions for the digital grid of the future. Our cutting-edge research expertise is supported by a state-of-the-art microgrid testbed, which will be used to trial the developed solutions and to translate them into business cases for network companies, retailers, DER aggregators and technology providers alike.

# 2. Situation overview

**Core power grid technologies were developed at the beginning of the 20th century, and the same model is primarily used today. The rapid development of digital technology, including ubiquitous computing, sensors, fast communications and IoT, requires a revolution in energy management, as electricity can be managed at small-scale DER and even home energy devices.**

## The prosumer and the challenge

In traditional energy grids, customers were simply energy consumers, and energy flow was one way from generation to load. Advances in rooftop solar and smart metering technology have enabled consumers to increasingly generate and sell energy, thus becoming prosumers, resulting in two-way energy and information flow. This trend is set to increase substantially.

The AEMO predicts small-scale rooftop solar can serve over 20 per cent of total energy demand by 2040[1]. As a result, the future generation mix will increasingly consist of geographically dispersed small-scale DER, primarily consisting of household and commercial rooftop solar and battery storage predominantly connected 'behind the meter'. This significant change cannot be supported by the current grid architecture designed for one-way energy and information flow[2].

Another challenge is balancing the increasingly variable supply, which requires storage. While storing large amounts of electrical energy is technically possible, it is also expensive. A smarter way of balancing variable supply is to reshape the demand by tapping the flexibility of prosumer-owned DER[3]. Many loads like hot water systems, air conditioners and pool pumps are inherently flexible but using them as a flexible resource has traditionally been challenging because of the impact on human comfort. The existing demand response program used for peak demand reduction are ill-suited for continuous load shaping. Nevertheless, with the emergence of rooftop solar and battery storage which decouples power and energy consumptions, and more importantly, intelligent energy management systems (EMS), using demand flexibility for system operation is now possible at a new level.

The energy market lags behind many other sectors which do take advantage of IoT technologies. Service providers and retailers such as Amazon, Alibaba, Google, Facebook, Airbnb and Uber, use digital technologies to run platform-based businesses, which bring together sellers and buyers. The business model of these companies is based on building and orchestrating networks of peers in which participants interact and share in the value creation and service delivery.

This model could be applied to energy trading by networking individual prosumers to create peer-to-peer (P2P) energy markets. While such markets provide a better value to rooftop solar owners who can sell their excess production to their neighbours, they are not suitable for using DER to provide grid support. Power electronics technology used to interface DER with the grid can control active and reactive power, for example, to smooth peak demand and to help stabilise the energy grid. However, to use DER for grid services, like voltage control and congestion management in distribution networks, and frequency control and load balancing in the wholesale market, they need to be *orchestrated*. This is achieved by aggregating massive DER in virtual power plants (VPPs) that behave as a single entity.

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1 AEMO, "Integrated System Plan", July 2020. (https://aemo.com.au/-/media/files/major-publications/isp/2020/final-2020-integrated-system-plan.pdf?la=en)
2 Energy Networks Australia, "Open Energy Networks Project", 2020. (https://www.energynetworks.com.au/resources /reports/2020-reports-and-publications/open-energy-networks-project-energy-networks-australia-position-paper/)
3 The Brattle Group, "The National Potential for Load Flexibility – Value and Market Potential through 2030", June 2019. (https://brattlefiles.blob.core.windows.net/files/16639_national_potential_for_load_flexibility_-_final.pdf)

## Digital energy systems

The innovative VPP concept is a potential solution for the decentralised, scalable two-way digital energy system, which will maintain the stability of energy supply and provide an open two-way energy market.

Digital and Internet technologies will transform the electricity network into a cyber-physical digital grid, where millions of internet-connected DER will actively participate in a real-time market akin to the world of e-commerce. Digital energy systems will use advanced analytics and AI to accurately predict who needs energy and deliver it at the right time with the highest efficiency and at the lowest cost. At the same time, the prosumer-driven energy supply will make it possible to operate parts of the network as microgrids, which will increase resilience and reduce the network augmentation cost.

Australia, with one of the highest per-capita consumption rates of electricity in the world, rapid acceleration of renewable energy generation and small-scale DER, is well-positioned to deploy commercially viable VPPs. This can help transform passive consumers into active prosumers, participating in delivering services tailored to their own needs, and providing services to the larger grid.

VPP pilots are in operation today, but there are technical and other challenges that need to be considered before the digital energy system can be fully realised including:

- market rules and policy requirements will need to adapt to accommodate new technologies.
- large-scale wireless communication networks with strict latency, reliability, and bandwidth requirements will need to be rolled out to connect massive DER.
- cybersecurity solutions will be required to reduce the vulnerability of edge devices to cyberattacks. A proposed solution is to develop pilot projects involving academia, industry and government agencies to advance and test new technologies.

# 3. Decentralised power system architecture

**Unlocking the potential of massive DER will require a different power system architecture.**

Figure 1 below illustrates the difference between the conventional *centralised* and prosumer-driven *decentralised* power systems, where the transmission and distribution networks are reduced to a single node for the sake of clarity. Note that the transmission network is meshed, while the distribution networks are typically radial.

In the conventional power system (left) energy and information flow in one direction, from large-scale power plants through the high-voltage transmission, medium and low-voltage distribution networks the down to consumers. With the increasing penetration of prosumers, the energy can also flow *upstream*, from prosumers to distribution networks. The prosumer-driven decentralisation of the energy supply will require a rethink of the conventional market structure. At the same time, the energy grid architecture should be transformed from the provider-consumer unidirectional model into a bidirectional energy and information model; this will require tight integration of the physical network with the digital communications network, turning the energy grid into a *cyber-physical network*.

Current market designs and business models prevent individual prosumers from participating in wholesale electricity markets as they are unable to meet the market requirements for energy reliability, availability and amounts. They therefore need to be coordinated by an *aggregator*.

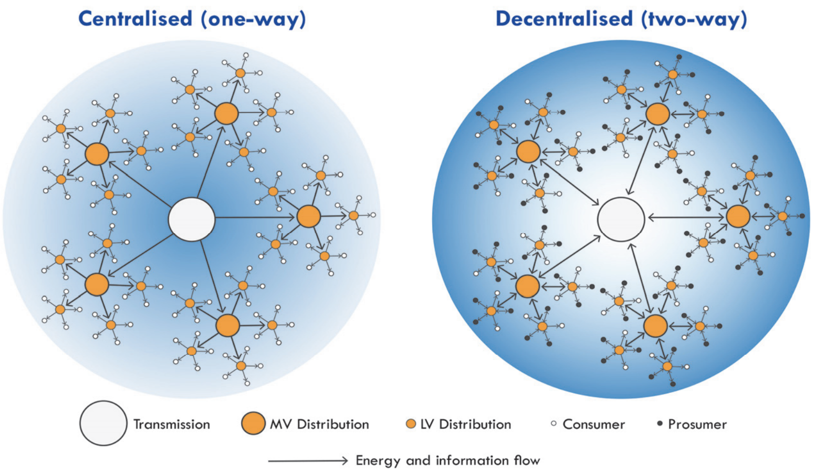


**Figure 1 Centralised (left) vs decentralised energy supply (right). MV and LV stand for medium- and low-voltages.**

Figure 2 compares the traditional market structure with the emerging market structure with active prosumer participation. In contrast to the conventional market structure with mostly passive consumers and electricity flowing in one direction only, prosumers can now sell energy and provide *network support services* in a *distribution energy market*. These services are used to support the operation of either the distribution grid (e.g. voltage control and congestion management) or the transmission grid (e.g. frequency control and load balancing).

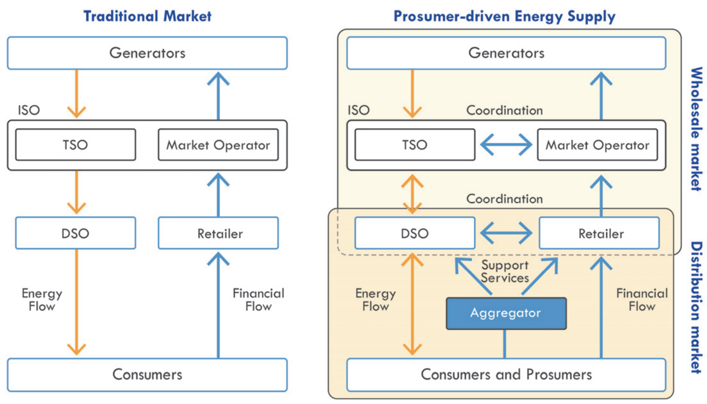


**Figure 2 Market organisation: traditional (left) vs prosumer-driven energy supply (right).**

## What we see as the challenge

The emerging challenge is, therefore, how to control the increasing number of prosumer-owned DER at the *grid edge*. The problem is not only their sheer number but also the fact that they can create voltage and network congestion problems, which requires *active grid management*. Two emerging concepts can provide a possible solution: the transactive energy systems framework and a new distribution system operator (DSO) construct. Notably, the retailer will need to coordinate the energy delivery with the DSO to ensure that the network constraints are satisfied. This is akin to the existing coordination between the wholesale market operator and transmission system operator (TSO). In some jurisdictions, they are part of the same company called an independent system operator (ISO).

Three market architectures are typically considered for DER aggregation, as illustrated in Figure 3, depending on where the *energy management computation* takes place and how market agents communicate among themselves:

- **Centralised architecture** - with a central computing entity that receives and manages all the information, e.g. existing power system control centre
- **Decentralised architecture** - in which the computational load is distributed among prosumer nodes in the power system and the interface entity that serves as a mediator or coordinator
- **Distributed architecture** - where the prosumer nodes perform all the computation locally and exchange information among themselves directly without a coordinator.

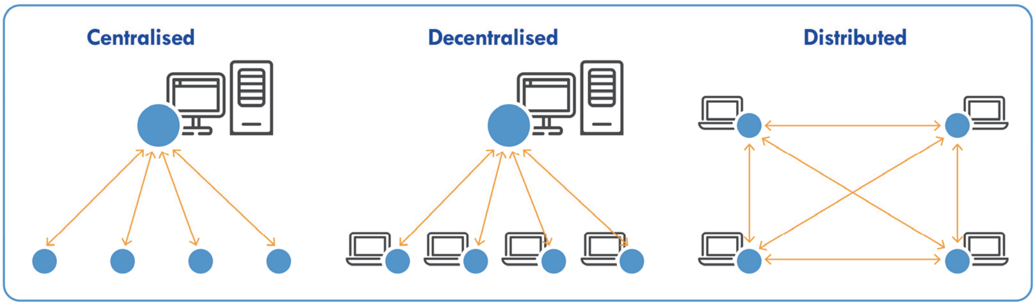


**Figure 3 Market architectures for DER integration.**

Specifically, the distinction between the market structures can be made based on the interaction between market agents and the approach adopted to supply energy and grid services:

- **Centralised structure** - prosumers interact with a central entity for example an aggregator or a retailer who oversees clearing the market using all the information provided by the prosumers.
- **Decentralised structure** - also considers the interaction of prosumers with an interface entity but prosumers have local computational capabilities so that the computation can be distributed among prosumer agents, but communication between agents is required to reach consensus. In contrast to the centralised structure, in the decentralised structure, prosumers do not have to reveal all their information. Instead, the coordination can be achieved using prices, which ensures that user privacy is preserved.
- **Distributed structure** - that does not require an intermediary. In this case, the allocation and prices are determined through direct negotiation among market agents.

# 4. Virtual Power Plants - unlocking DER potential

**A VPP connects geographically dispersed DER, including batteries, flexible loads, renewable and non-renewable generation sources, by communication networks, either embedded, shared or hybrid.**

A conceptually similar approach for grid integration of DER is a microgrid. The critical distinction is that a microgrid has clearly defined electrical boundaries, typically as a distribution subsystem installed behind the power meter for a specific consumer. Examples include precincts, fringe-of-grid and isolated energy systems supplying remote communities, and household microgrids. Another critical distinction is the ability of a microgrid to operate in an islanded mode, disconnected from the primary grid[4]. A microgrid can support the operation of the primary grid through the exchange of active and reactive power for regulating voltage and frequency of the local network.

In countries with low population density like Australia, electricity grids span vast distances to supply geographically remote communities; this is not only costly but can also be unreliable due to frequent grid outages. An option is to turn these *fringe-of-grid* load centres into microgrids, which reduces not only the operational cost but also the capital cost due to the avoidance of network augmentation. The existing grid connection, however, remains operational, which offers an exciting opportunity to connect several microgrids into VPPs, where microgrids take over the responsibility for providing network support.

VPPs enable the management of flexible energy capacity on a large scale, by controlling the energy generation, storage and consumption in real-time. The problem falls within the domain of the IoT, where potentially millions of Internet-connected devices collect and exchange data to achieve a common objective. Large-scale VPP deployment will result in higher reliability, better efficiency, and economic benefits, by allowing DER owners to harness additional value streams by offering grid support services.

As conceptually illustrated in Figure 4, a virtual power plant consists of:

- A VPP coordination platform that coordinates and optimises network and market operations
- A hierarchical communication network that connects all VPP components, energy grid control centre, and electricity market
- Utility-scale DER, including solar and wind farms
- Prosumer-owned DER
- Flexible loads such as electric carparks.

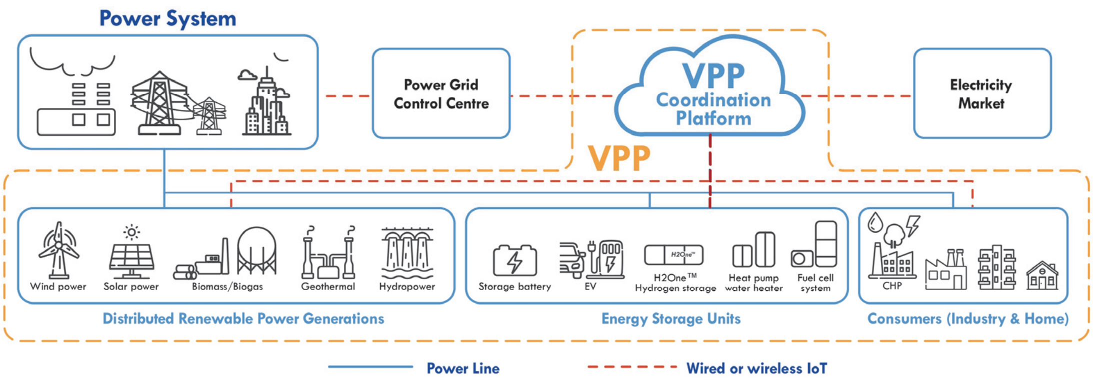


**Figure 4 Conceptual diagram of VPP.**

The VPP management system coordinates network and market operations. The network service is delivered by an IoT-based energy management system that uses the data from the connected VPP participants to monitor and control energy generation, consumption, and storage in real-time along an optimised schedule. The real-time data on the network capacity utilisation are also used to generate forecasts for electricity trading. The communication network connects individual VPP nodes via secure data links and transmits data and commands between the nodes and control units in the IoT system.

4 CIGRE Working Group C6.22, "Microgrids 1 Engineering, Economics, & Experience", 2015.

The VPP concept has attracted widespread attention of both academic researchers and, industries worldwide. This is due to its strong capabilities and its distinct advantage of simultaneously providing optimal network and market services. Compared to the early VPP applications that focused on utility-scale DER, connected to the transmission grid, the new generation of VPPs concentrates primarily on small-scale DER. There is a growing list of operating prosumer-based VPPs globally in Europe, Japan, USA and Australia.

The existing VPPs, however, do not fully exploit what DER can offer. State of the art is to directly control individual batteries to improve the VPP operator's position in the wholesale market. The interest of the battery-owner is only considered implicitly through a fixed monthly payment. On the other hand, digital and communication technologies can enable a proper two-sided market where VPPs both trade in the wholesale market and offer network support services to increase the hosting capacity of distribution networks.

The recently completed ARENA funded Bruny Island Battery trial[5] where the University of Sydney played a significant role is an example of how innovative use of communication and distributed optimisation technology can push the boundaries of what DERs can offer.

# 5. AI-based energy management and optimisation

**Digitisation required for massive DER orchestration will permeate all aspects of power system operation. Importantly, using the conventional model-based approach for power system control will neither be practical nor possible due to the sheer number of agents with only partial observability. Instead, a *data-driven* approach will be required, supported by *data analytic* tools for processing massive amounts of smart meter and sensory data to extract useful information.**

Data mining techniques, such as pattern recognition and clustering, can be applied to discover consumers' electricity consumption behaviour patterns hidden in smart meter data. Deep neural networks assess the load and generation forecast based on data collected from energy IoT smart devices, including meters, inverters, appliances and thermostats to provide information that can be used to assess the load and generation forecast. This knowledge can help evaluate the demand response potential of individual consumers, which can inform VPPs to exploit demand flexibility more effectively. Based on this knowledge, customer selection can be optimised synergistically with other resources (e.g. battery storage) in the VPP resource planning stage to increase asset utilisation efficiency. Also, knowing how customers respond to dynamic pricing or incentive can be utilised to inform the design of demand response programs.

Edge computing architecture for real-time data stream processing is used to meet real-time quality of service (QoS) requirements of the provided services and addressing the unexpected transmission latency caused by Internet connections. The architecture is based on a large-scale hybrid cloud system, which combines edge and cloud computing. The edge computing is responsible for clustering analysis and prediction by mining the underlying data from the prosumers units. Cloud computing is used to achieve the overall objective optimisation.

5 https://arena.gov.au/projects/consumer-energy-systems-providing-cost-effective-grid-support-consort/

### How do we coordinate massive DER?

In data-driven power system operation, machine learning is used to predict user behaviour and weather patterns to get an accurate forecast of demand and generation used in market dispatch, respectively. Market dispatch is an optimisation procedure that determines the generation schedule to serve the demand at minimum cost, which is solved as a single optimisation problem in the conventional market operation.

By contrast, optimally dispatching massive DER will require a distributed optimisation approach. In this approach, the solution is found iteratively, whereby each agent solves its own subproblem in each iteration and communicates the solution back to the central entity. The agent subproblems can be solved on a single-board computer embedded in an EMS of the user agent, which can be a smart meter. In the distributed implementation, the computation burden is spread among agents and thus is independent of the problem size, which ensures scalability. Also, DER agents only exchange information of total consumption with the central entity and do not have to reveal the operation details of individual devices, which preserves user privacy.

However, DER are connected to distribution networks with operational constraints vastly different to transmission networks. In the days of one-directional energy supply, distribution network constraints were not an issue, but now they need to be considered in DER dispatch. That will require a hierarchical approach where DSOs and microgrid operators will take responsibility for ensuring that local network constraints are not violated, while the transmission system operator takes care of the transmission network constraints as before. Electricity network constraints can be introduced into the DER coordination problem, resulting in a model akin to the optimal power flow problem used in the wholesale market. This approach has been successfully trialled in the recently completed ARENA-funded Bruny Island Battery Trial.

# 6. Need for VPP Communication networks

**The data-driven DER management and control will require reliable, pervasive, and scalable communication networks. Large volumes of data will be collected, shared, and analysed across the digital energy systems, VPPs, microgrids, grid control centre and electricity market.**

Traditional energy grids use separate communication networks to support automation, protection, and metering services. As new digital grid services start to emerge, for example, distributed automation, automated demand response, grid condition monitoring, the existing practice of purpose-built disparate communication networks will not be economically feasible[6]. General communication network infrastructure, supporting all DER aggregation and network support services, will be required.

### Smart use of the technology

A communication network architecture for a VPP system is shown in Figure 5. In the existing smart grids, all the data from devices and grid equipment are sent for processing in the central cloud. With a massive number of IoT sensors deployed in the grid, vast amounts of

6 K. C. Budka and J. G. Deshpande, "Utility of the future – a Bell Labs perspective," in Conference of Power and Electricity Supply Industry, 2018.

data are generated, and their transmission causes significant network delays and bandwidth usage. To improve the response times and save network bandwidth, edge computing will be used for local traffic processing by bringing cloud computation facilities and storage closer to the data sources. In the VPP system architecture, the edge carries out real-time control for time-critical operations in the grid, while the central cloud performs higher-level information processing, data analytics, and visualisation.

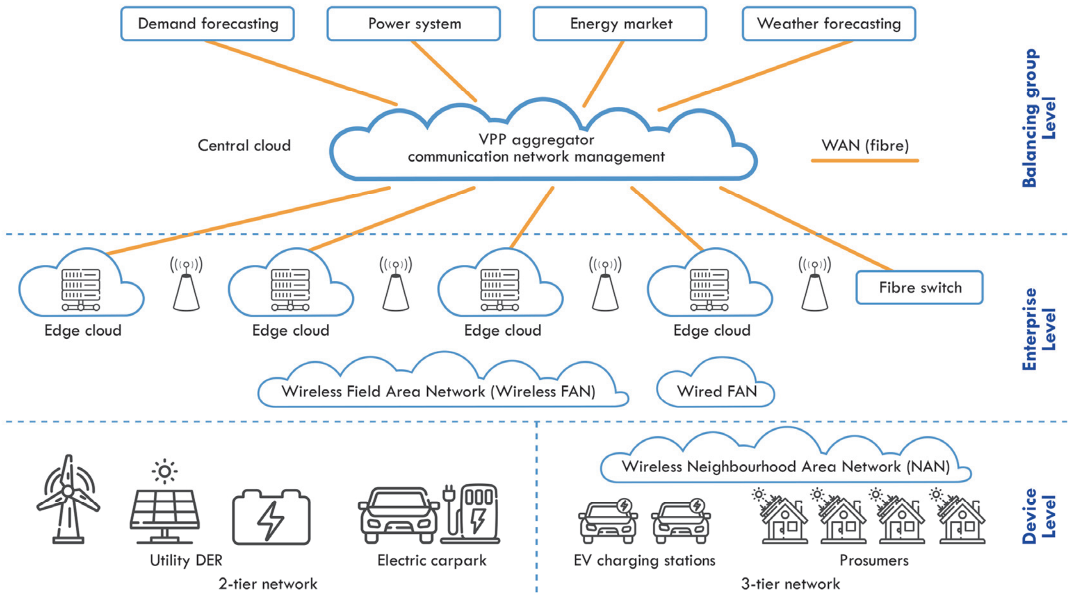


**Figure 5 VPP communication network architecture.**

The VPP communication network architecture is arranged in three levels the:

- balancing group
- enterprise
- device

## Three communication layers - WAN, FAN and NAN

VPP consists of a wired (typically optical fibre) wide-area network (WAN) and the *last-mile network* split into field-area network (FAN), and a neighbourhood-area network (NAN).

NAN is used for short-range communication from end devices to a local concentrator and is not needed in many instances. FAN connects local field device to the backhaul (e.g. a base station). For example, for a smart building, a NAN connects devices within each apartment, such as heaters, refrigerators, and air conditioners to the apartment level energy controllers.

In contrast, FAN connects the apartment level energy controllers to the building energy edge controller at the enterprise level. For individual homes with rooftop solar, solar inverters may be connected by a NAN directly to the energy edge controllers. The coverage for a NAN will be less than 1 km while the FAN range could be of the order of tens of kilometres. Wireless networks are preferred for the last-mile network due to their low installation costs, flexible access and scalability. Utility-scale DER and larger loads are connected directly to the field area network (FAN) in a 2-tier structure, while smaller DER, including prosumers use a 3-tier structure with an intermediate neighbourhood area network (NAN).

WANs, FANs and NANs have specific requirements in terms of bandwidth, reliability and latency, as shown in Table 1.

| Network Types | VPP Level | Applications | Latency range requirements |
|---|---|---|---|
| **Wireless or Wired FAN** | Enterprise Level | Pricing | < 1 min |
| | | Demand Response | < 1 min |
| | | Electric transportation (e.g., pricing info, charge status) | < 15 secs |
| | | Intelligent distributed feeder automation | msec |
| | | DER management | msec |
| **Wireless NAN or FAN** | Device Level | Building automation | sec |
| | | DER control | msec - sec |
| | | Distributed intelligent electronic device (IED) and distributed automation (DA) | msec |
| | | Millisecond-level precise load control | msec |
| **Wide Area Network (WAN)** | Balancing Group Level | Adaptive islanding | < 0.1 sec |
| | | Voltage control | < 5 msec |

**Table 1. Communication requirements of FAN, NAN and WAN for different VPP applications**

One of the biggest roadblocks for the integration of various assets into a VPP is that the existing communication technologies are rigid and have low capacity.

Low range communication technologies, such as Zigbee, WirelessHART, Bluetooth, and WIFI can achieve relatively low latency, but the range is very short, and the number of devices which can be reliably connected within each network is limited. Because they operate in the unlicensed spectrum, their performance cannot be guaranteed. Therefore, they can be used for NAN applications, which do not have strict QoS requirements.

For FANs, there are some proprietary long-range communications technologies operating in the unlicensed spectrum, such as SigFox, LoRa, Weightless and RF-mesh networks. Their performance cannot be guaranteed, and they have very low data rates. Moreover, they are *proprietary* wireless RF *technologies*, which pose interoperability issues.

Cellular networks ensure a cost-effective strategy for connecting VPP nodes over a wide geographical area and guarantee technology evolution in alignment with long life-cycle considerations of the utility sector. Cellular networks present the most suitable choice for last-mile networks. Some VPP scenarios and services could be supported by 4G cellular networks.

The current 4G cellular networks have typical reliability of 99%, in terms of packet success rate within a time period. The average latency is about 100ms, which is unpredictable and can go up to several seconds, and thus cannot meet the requirements of time-critical applications, such as power electronics control, distributed feeder automation, and fault detection, isolation, and restoration. These applications require guaranteed consistent ultralow latencies two to three order of magnitude lower than those in 4G networks. Latency and jitter, and consequently, packet loss in 4G networks also influence the performance of some VPP services[7].

In summary, VPP communication networks will need to enable multiple applications with very diverse performance requirements. The current 4G cellular network cannot support different

7 M. Zajc, M. Kolenc, N. Suljanović, “Virtual power plant communication system architecture”, Smart Power Distribution Systems, Academic Press, 2019, pp.231-250.

applications on single network infrastructure. This means that a separate network should be deployed for each application. This approach involves multiple communication networks that must be managed and maintained, increasing operational costs. 5G Software Defined Networks (SDN), and network slicing technologies enable sharing of multiple applications on single network infrastructure, each optimised for its specific service. Therefore, 5G networks with the capability of network slicing, SDN, and edge computing are the most suitable communication technology to support multiple digital grid applications and sustain ultra-high reliability, low latency, security, scalability, and interoperability.

VPP last-mile networks can be deployed with public cellular networks, operated by telecom operators. As 5G networks can operate in the licensed, unlicensed, and dedicated spectrum, VPPs could be supported by their own private networks, operating either in the unlicensed or dedicated spectrum. Private networks could provide better performance and security than those of public networks. They can be custom designed for specific applications, be easily configured for higher-speed and better performance. They will be controlled by the VPP operator and could be reconfigured.

# 7. Cyber-physical security

**Cyber-physical security of digital energy systems is a critical consideration due to the use of large-scale distributed computing and communications technologies.**

Cyber vulnerabilities have been identified in various facilities of energy grids, including the supervisory control and data acquisition (SCADA) system that energy grids rely upon for real-time monitoring and control of the physical grid. The increasing DER penetration also creates multiple entry points for distributed cyber intrusions that are challenging to detect, predict, and prevent. Smart meters and other low-complexity sensing devices at customer locations, with data collection capabilities for billing, outage reporting, and other customer operations, will need built-in security protection to avoid data privacy leaks and other attacks.

## A possible solution

A possible solution to increase cyber-physical security is to use lightweight security protocols in DER aggregation. AEMO recently developed a Cyber Security Framework to assess the cybersecurity maturity and security profile of all energy participants[8]. The framework provides a comprehensive overview of potential cybersecurity risks and the evolving threat landscape faced by the Australian energy sector. In VPPs, key concerns include rigorous identity and access management to prevent unauthorised user activity, enhanced multi-layer network security focused on wireless security, and robust personal information and privacy management to protect sensitive individual user data.

Identity and access management is challenging in VPPs due to a wide range of devices and edge servers accessing the network. Scalable blockchain designs based on lightweight smart contracts have been proposed to facilitate identity and access management in large-scale distributed networks such as VPPs. They have been shown to prevent more attacks with faster processing times and low end-to-end delay compared with conventional Bitcoin and Ethereum schemes[9].

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8 AEMO, "Australian Energy Sector Cyber Security Framework", 2019. (https://aemo.com.au/initiatives/major-programs/cyber-security/aescsf-framework-and-resources)
9 A. S. Sani, D. Yuan, W. Bao, P. L. Yeoh, Z. Y. Dong, B. Vucetic, and E. Bertino, "Xyreum: A High-Performance and Scalable Blockchain for IIoT Security and Privacy", IEEE International Conference on Distributed Computing Systems (ICDCS), Dallas, Texas, USA, July 2019.

In VPPs, a comprehensive multi-layered approach to network security is necessary to ensure different wireless technologies used to support communications are not compromised. At the transport layer, cryptographic key-exchange protocols, such as the internet-based transport layer security, should be implemented to support end-to-end secure communications over distributed networks. At the physical and medium access control (MAC) layers, fundamental characteristics of the wireless channel and mobile edge computing architectures can be harnessed to provide security against various attacks, such as eavesdropping, jamming, and spoofing[10]. Network slicing can also provide additional security benefits of flexibly identifying and isolating critical communications for operational systems, IT systems, and network traffic during a security incident.

### Privacy management

Privacy management will be paramount to ensuring widespread VPP participation by energy users. The heterogeneous VPP structure can be used to aggregate user data at the edge servers and remove personally-identifying information before transmitting it to the central VPP controller. Information leakage between multiple sources communicating over a shared wireless channel can also be characterised using fundamental concepts from information and communications theory.

# 8. Market design and policy framework for Digital Energy Systems

**The existing market framework that reflects the centralised power system structure has remained mostly unchanged since its introduction more than twenty years ago. With the transition to a decentralised energy supply dominated by small-scale DER, market design and policy framework will need to adjust to support DER aggregation to reward their value and contribution in power system operation.**

The future market design will incentivise DER investment, which will address the energy trilemma: increasing economic efficiency, reducing carbon emissions and improving grid security.

Digitisation, underpinned by big data analytics, AI, ubiquitous communications and blockchain technologies will support distributed energy markets (see Figure 2) where prosumers trade energy and provide grid services in VPPs and microgrids. Consumer participation is enabled by automated demand response, where *customer-facing network-aware* EMS optimise DER operations considering both the value to the DER owners and the operational requirements of the network.

Today, network service providers operate in a non-competitive environment that rewards them for increasing their regulatory asset base but does not incentivise innovation. Using VPPs to support network operation, while reducing the cost for DER owners, will thus require a significant shift in the current regulated cost-plus-compensation model. To realise the opportunity presented by the technical capability of network-aware VPPs, the regulatory framework will need to shift towards a model that encourages the provision of new products and services. Network companies will therefore need to work together with DER aggregators and retailers to facilitate distribution energy markets with full prosumer participation. The

10 Y. Zhuo, C. Pan, P. L. Yeoh, K. Wang, M. Elkashlan, B. Vucetic and Y. Li, "Secure Communications for UAV-Enabled Mobile Edge Computing System", IEEE Transactions on Communications, vol. 68, pp. 376 – 388, Jan. 2020.

newly developed market platforms will enable the monetisation of new products and services across the value chain.

To address this, the Australian Energy Market Commission (the 'rule maker') has recently introduced two essential rule changes: Wholesale Demand Response Mechanism[11] that will enable market participation of small-scale DER aggregated into VPPs to bid directly into the wholesale market, and Five Minute Settlement Rule[12] that will provide a better price signal for investment in fast response technologies, such as batteries, and VPPs.

In parallel, the Energy Security Board proposed seven market design initiatives, including a long-term approach towards two-sided market arrangements[13] and initiatives to facilitate DER market integration to enable DER to participate in multiple markets and service provision (value stacking).

# 9. The University of Sydney Microgrid Testbed

**The Real Time Digital Simulator (RTDS) is a power grid simulator that can emulate the behaviour of a physical grid in real-time. It can connect external physical devices through either digital or analogue inputs, including protection relays, energy management controllers and DER.**

The testbed is a flexible hybrid cyber-physical power system model shown in Figure 6. It is based on a combination of RTDS and several physical devices connected to a software-defined virtual network (SDVN), providing wireless connectivity that can support both centralised and distributed control architectures.

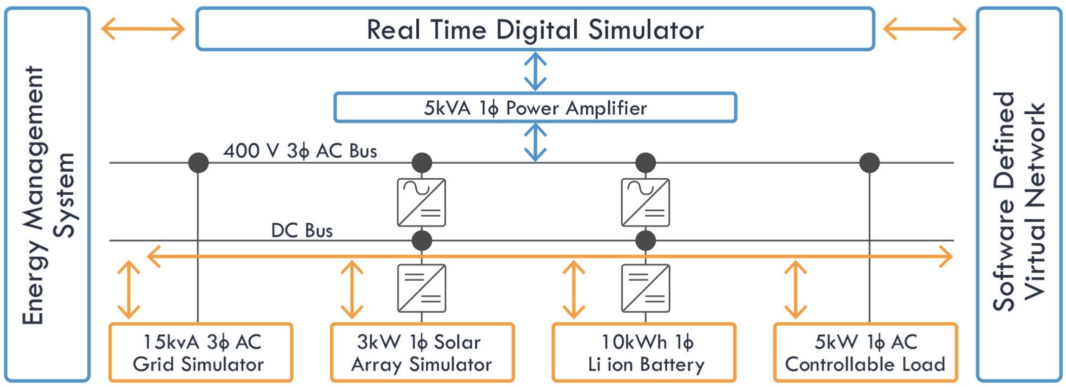


**Figure 6 Microgrid testbed.**

The power amplifier serves as an interface between grid simulation and DER by converting the DER power output into a low-power signal fed into the RTDS. Such hardware-in-the-loop simulation allows replicating real-life conditions in a laboratory environment.

11 AEMC, Wholesale demand response mechanism (https://www.aemc.gov.au/rule-changes/wholesale-demand-response-mechanism)
12 AEMC, Five Minute Settlement (https://www.aemc.gov.au/rule-changes/five-minute-settlement)
13 The Energy Security Board, "Post 2025 Market Design Consultation Paper", September 2020. (http://www.coagenergycouncil.gov.au/sites/prod.energycouncil/files/publications/documents/P2025%20Market%20Design%20Consultation%20paper.Final_.pdf)

The testbed can support both 3-phase AC and DC voltages, which allows the simulation and testing of various network topologies, including islanded and grid-connected microgrids, precincts embedded networks and virtual power plants. The 3-phase AC supply is provided either from the mains or from a programmable AC voltage source, which allows simulating various network disturbances.

The physical devices include a rooftop solar emulator, a programmable load and a Li-Ion battery storage unit with associate inverters, controlled by an EMS. The setup is fully configurable, including rooftop solar generation profile, demand profile and EMS optimisation objective, and can thus model a realistic household microgrid. The EMS is implemented on a single-board computer that runs the optimisation algorithm and communicates with other devices.

SDVN provides integrated real-time wireless and wired communication networks, fully reconfigurable by using software modules at the data centre. The software modules at the data centre, referred to as Mobile Central Office Re-architected as a Datacenter (M-CORD) are based on an open and programmable network hardware platform. SDVN consists of three distinct components:

- access network that connects Smart Grid sensors in RTDS and/or in physical equipment to the base stations
- multiple open-source network switches and fixed transmission links that connect multiple base stations to the SDVN management centre
- the centralised controller in the data centre that manages the whole network.

The testbed will be used to test different use cases, including:

- VPP energy management on a time scale of minutes, requiring low latency and potentially high-bandwidth communications
- provision of fast services, including frequency and voltage support, requiring high latency and low bandwidth communications
- peer-to-peer energy trading.

# 10. Conclusion

An unprecedented opportunity exists for the Australian energy sector to decide on how it will transform to meet the current and future market needs.

Change will no doubt be disruptive, but it will occur, as it did with new business models in other industries such as transportation, accommodation, and finance. Change is in fact already occurring in the sector. Electricity distribution is moving to a two-way market, digitisation including technologies such as IoT, low latency communications are supporting change to digital energy systems, while fresh commercial opportunities with prosumers are being investigated through new modelling.

The University of Sydney's Centre for Future Energy Networks and Centre for IoT and Telecommunications are at the forefront of this change and world leaders in new modelling of the power and IoT industries. This paper is a high-level summary of the plans for change. We invite you to join us on this journey for change.

To discuss, or for more information about the contents of this White Paper please contact Faculty of Engineering, School of Electrical and Information Engineering:


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