Blockchain in Energy: A Look at the Future Grid

Powerledger

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Executive Summary: Blockchain and the challenge of renewable energy

Ever since the introduction of renewables onto the grid, there have been associated and anticipated problems: issues such as intermittency, minimum demand and inertia, deficits and congestion. These problems have become all too clear in recent years, with the cost of running ancillary services, the work that keeps the grid stable, increasing significantly. While the traditional response to this is to build bigger, and more infrastructure, the cost of this along with the lack of scalability has led many to realise that a distributed grid is the sensible solution as renewable penetration increases.

After the decentralisation of the production of electricity, there are a couple of further questions.

Should the grid's accountancy systems be run in a centralised or decentralised way? This issue is the focus of this paper. Should they keep tabs on who owes what to whom, use a decentralised technology like blockchain or instead opt for a more traditional database system? The paper also looks at how blockchain may become a recognised standard of data interchange, like smtp, http, and EDI.

There is also a related question about authority. Should the controlling authority that is responsible for the grid behaving properly and not combusting into flames, power shorts and explosions, also be centralised? Or, to what extent can it be negotiated by dynamic agreement between the various parties? Such a question might even take in the issue of inertia: Should synthetic inertia be coordinated by a centralised agreement or a decentralised one?

Along with the production of renewables comes the topic of sustainability reporting and trading of environmental commodities through RECs - renewable energy certificates, and carbon credits. While separating the energy attributes from the energy itself helps the energy transition to take place, this has led to several instances of greenwashing and fraud due to a lack of transparency.

This paper concentrates on the accountancy of a decentralised network for transactional trading of both energy and environmental commodities and asks how the grid of the future might involve a convergence of the various markets that currently define its hours, days and weeks ahead, and how they might become increasingly real-time in character.

In this world that we believe is fast approaching, the consumers and prosumers become increasingly responsible, de-facto, for the balancing markets that make a grid work. Frequency response, reserve, reactive power and system restoration have become 'democratised'. Just as the advent of the smartphone created more than just a camera on a phone, and opened up an era of social media, this paper suggests that we can expect a plethora of new services that solve old problems, together with some new ones.

1. Problems in power grids and the decentralised imperative

As a centralised system, the grid has served us very well for a number of years. Since the 1920s in the US and UK, when different power stations began to become integrated into the grid, the stability of the grid was never in doubt.

However, as renewable energy resources have come onto the grid, their variability has posed a challenge for the engineers because they lack the prime quality needed to contribute to a centralised grid: a stable predictable output of power.

One of the recurrent themes of this paper is that of centralised versus decentralised systems. A fuller exploration of attributes of centralised systems can be found in the appendix but in general centralised systems suffer from six problems: having a single point of failure, a lack of transparency, a vulnerability to attack, limited scalability, a lack of user control and perhaps most importantly, a poor ability to allocate complex resources, especially variable ones.

This is true beyond engineering and continues in the economics and political domain too. History has shown that the poor allocation of resources in super-centralised nations has resulted in challenges in meeting the needs of their populations.

The problem with allocating resources is found everywhere variable distributed resources occur. A perfect example might be California, USA. One might imagine that as solar power becomes better established in the state, and as pressure to reduce carbon-sourced energy ramps up, variable renewable resources (VREs) would become better integrated into the California grid and costs of electricity would be reduced. However, this does not appear to be the case. The chart below shows how curtailment, i.e. switching off renewable energy sources from the grid, is increasing, year on year, with peaks every spring. This continuing curtailment, apart from wasting energy creates disenchantment for solar owners and reduces further investment. The levels of curtailment suggest that we have some important understandings yet to gain, and new solutions to include if we're going to successfully integrate renewables onto the grid.

It's also worth noting that California's reliance on crude oil is increasing, and so is its mismanagement of renewables, such as renewable curtailment.

The California Energy Consumption Report [1] clearly illustrates a notable increase of 34% in California's crude oil imports from 2020 to 2022. Further, from Figure 1[2], it is also clear that renewable energy sources were heavily curtailed t from 2020 to 2022. Further, the California

[1] Foreign Sources of Crude Oil Imports to California
[2] https://www.linkedin.com/pulse/electric-production-consumption-california-between-matteo-putzulu/

Energy Commission[3] says "*Natural gas continues to play an important and varied role in California. Nearly 45 percent of the natural gas burned in California was used for electricity generation*".

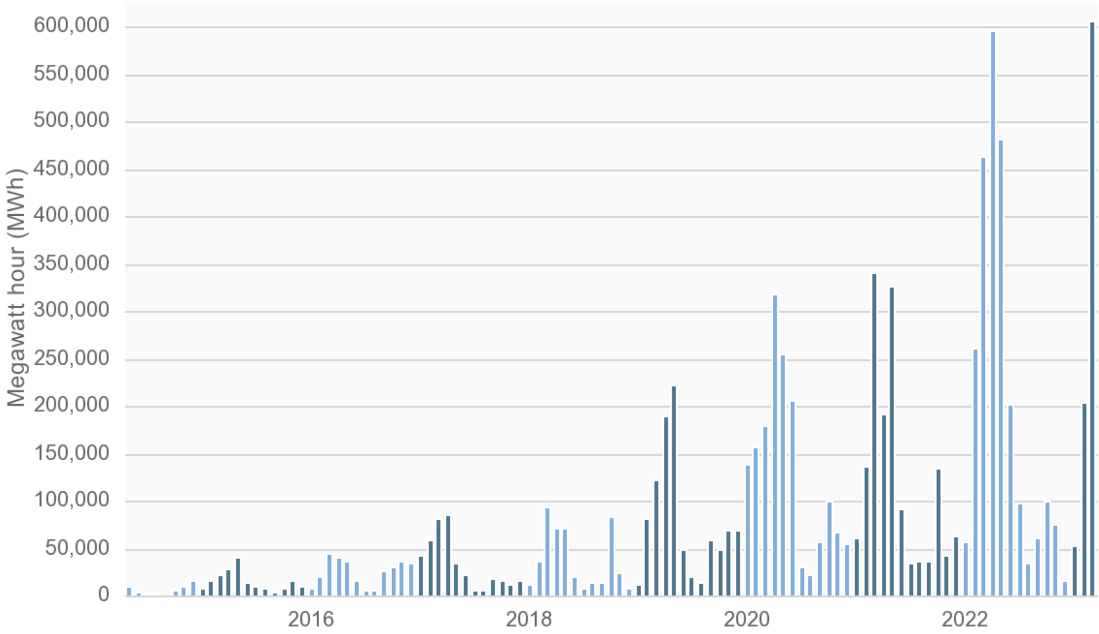


Figure 1: The total curtailment of variable energy resources by month in the California Independent System Operator (CAISO)

All of these factors have very likely resulted in increased costs for centralised power management. Some reports say that these costs increased every year by about 7.7% [4].

So the evidence suggests that having plenty of solar panels and a sunny climate does not always equate to having cheap electricity.

If you look at the European picture this relationship shows a more disturbing trend. In Figure 2 below, it is possible to correlate high levels of VRE with high costs of energy in both the domestic and industrial sectors.

Similarly, the Duck curve - which details the problems of uneven solar energy production over the daily cycle - has generally become increasingly deep.

These problems speak of the challenge of integrating renewable electricity onto the grid and can be traced back to two more fundamental issues: problems to do with intermittency (time), and problems of place (spatial). Both of these reflect the difficulties of balancing a grid where the urge to place renewable sources has overwhelmed the system's ability to plan for them correctly. There is a third problem that arises from increased usage of VRE, and that is inertia, but that has yet to become critical and will be dealt with in more detail later.

[3] https://www.energy.ca.gov/data-reports/energy-almanac/californias-natural-gas-market/supply-and-demand-natural-gas-california
[4] What Can You Do About Rising California Electric Bills? (solartechnologies.com)

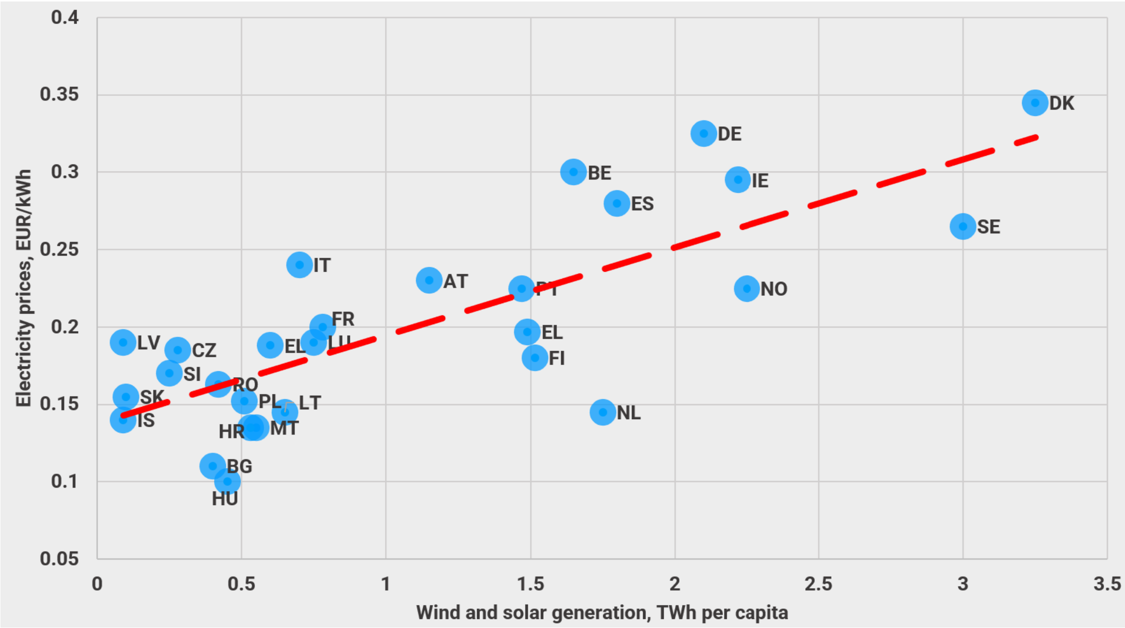


Figure 2: Household electricity prices vs. wind and solar penetration in Europe by country ([JPMAM. 2022][5])

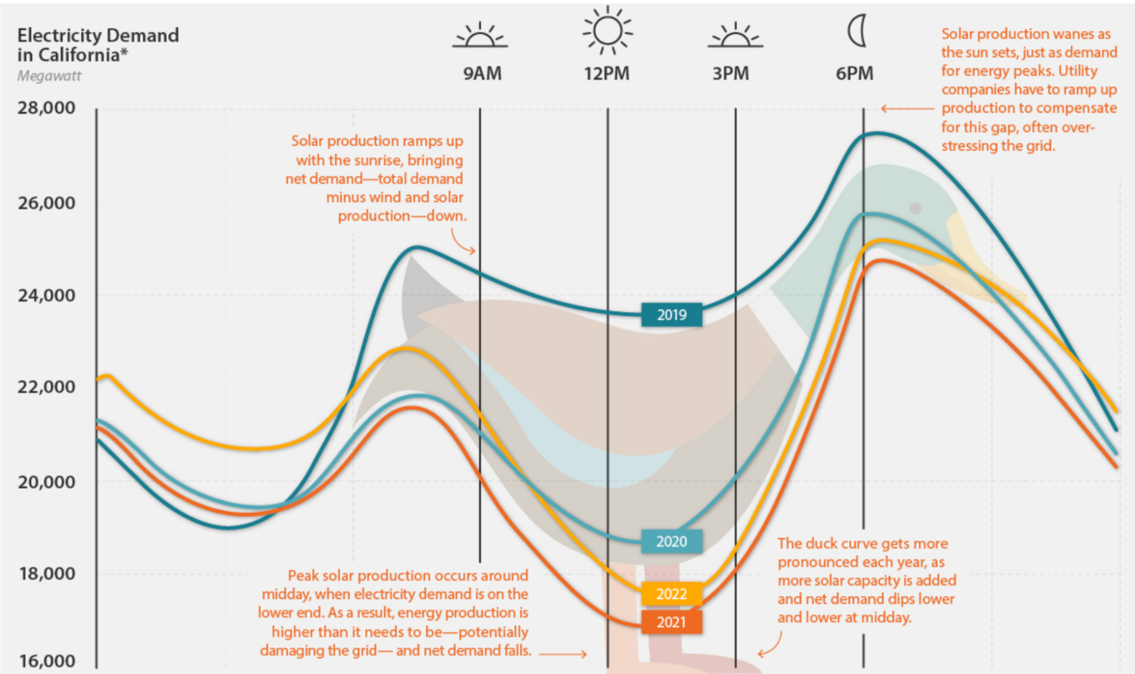


Figure 3: Duck curve showing uneven solar energy production[6]

[5] [J.P.Morgan Annual Energy Paper (2023): https://assets.jpmprivatebank.com/content/dam/jpm-wm-aem/campaign/energy-paper-13/growing-pains-renewable-transition-in-adolescence.pdf](https://assets.jpmprivatebank.com/content/dam/jpm-wm-aem/campaign/energy-paper-13/growing-pains-renewable-transition-in-adolescence.pdf)

[6] https://elements.visualcapitalist.com/the-solar-power-duck-curve-explained/

1.1 The spatial issue

Blunt price signals caused by subsidies and high feed-in tariff rates have resulted in an indiscriminate building of VRE at locations unsuitable from a power-system perspective, as they are spatially distant from load centres.

A perfect example of this is when some form of state subsidy or political initiative has spawned a huge number of wind turbines where the wind strength is high but happens to be a long way from an appropriate grid entry point, leading to something like a stranded asset. Examples include trying to place wind turbines in the American midwest that have great potential but that are far away from the load centres, like New York or California.

Without building extra capacity, it may well be that those turbines become essentially stranded assets. Sure, they are creating lots of electrical energy, but the cost of building a sufficiently robust connector to bring that power to market can be unaffordably high.

With very centralised thinking, this kind of problem is surprisingly commonplace, and it explains why electricity prices are often pushed up rather than reduced by the introduction of more variable renewable energy resources on the grid.

1.2 The temporal issue

Just as injecting excessive power at the wrong part of the grid creates problems, so too does putting in excessive power at the wrong time.

The most obvious manifestation of this is the Duck curve. When many solar panels are operating on the same patch, driven by the same solar diurnal variation, the result is too much power at midday and not enough after 18:00. This means electricity effectively has a negative value at these maximum points, which is one of the reasons California curtails as much as it does.

The obvious solution, in a perfect world with lots of cheap lithium, would be to build huge amounts of battery storage and the temporal and spatial problems would all but disappear. However, in the absence of a perfect world, more subtle approaches need to be tried.

1.3 Distributed, P2P and local electricity markets

The fundamental problem when adding solar and wind to a grid is that the solar and wind farms are not a like-for-like replacement for their fossil-generating forebearers.

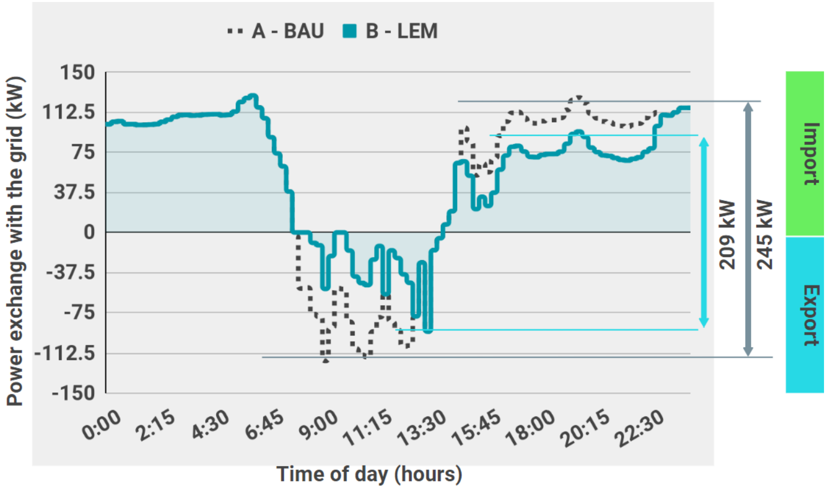
Their need for large geographically feasible areas (with high wind or high solar penetration) typically puts them in places far away from where their loads will be stationed. Also, their intermittency makes them quite hungry for expensive ancillary services that balance the grid.

To solve this problem, a decentralised model of an electricity grid is now seen as the way forward, where distributed energy resources (DERs) play a significant role in balancing the supply and demand at the distribution network levels. typically downstream to a substation, feeder or transformer.

In the decentralised model of electricity, the emphasis on centralised generation is replaced by a much more localised model, with neighbours, or peers sharing their excess solar power, and possibly battery resources.

If you consider an electrical community with a thousand households, it's possible to see that the average distance any packet of electrical power travels will be reduced if power is kept in the neighbourhood. In the Peer-to-Peer (P2P) model peers can sell their electricity to each other at predetermined prices or at any price they chose, at 5-minute intervals.

(a)



(b)

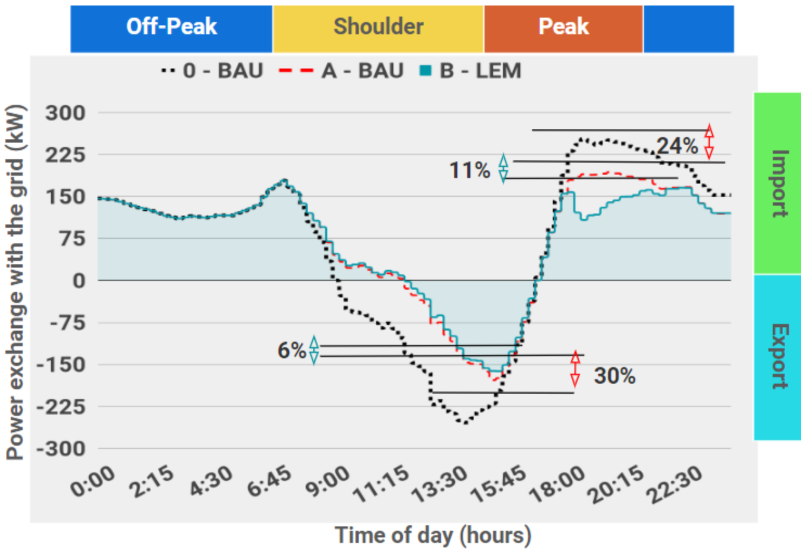


Figure 4: Power exchanged with the grid (a) Indian project with CBESS, and (b) Australian project with RBESS. Both show a significant reduction in grid import/export due to LEM. Source: Author's own work.

This flexibility of pricing is believed to be the key to a successful local energy market where issues of supply and demand can ultimately be resolved by price movement.

Studies of peer-to-peer networks like those done with Pebbles in Germany and Powerledger's own work, suggest that peer-to-peer sharing and variable pricing can have beneficial effects for the stability of the grid. Most notable is that the import and export of energy onto the greater grid is reduced. This means that a decentralised network of peer-to-peer energy-sharing communities could reduce the capital expenditure required by grids to maintain levels of system stability.

1.4 A case history from India and Australia

Figure 4(a) represents a Local energy market (LEM) with a Commercial Battery Energy Storage System (CBESS) from a project in India. Business as Usual (BAU) does not include CBESS and B) includes CBESS in LEM. In Figure 4(a), comparing Scenario A and B, the maximum difference between the solar export peak and evening demand peak is reduced by 36 kW through the LEM trading the CBESS. Solar export through reduced by 22.9 %, and in the evening demand peak was reduced by 7.6 %.

Figure 4(b) shows Residential BESS (RBESS) and LEM from a project in Australia. BAU does not include RBESS, B) includes RBESS and C) includes RBESS with LEM. When compared to a system with PV/RBESS versus PV/RBESS with LEM, the results show a reduction of the export peak by 6% during midday and a reduction of the evening peak by 11%.

The above results show that the utilisation of behind-the-meter RBESS or a CBESS in a distribution system can be enhanced through a P2P trading-based LEM platform which reduces the grid export and import by further and leads to larger deferral or avoidance of CapEX and OpEX.

LEMs and P2P networks could help reduce the cost of electricity. For this reason, decentralised electricity networks are regarded as the most renewable-friendly way of getting more sustainable energy onto the grid.

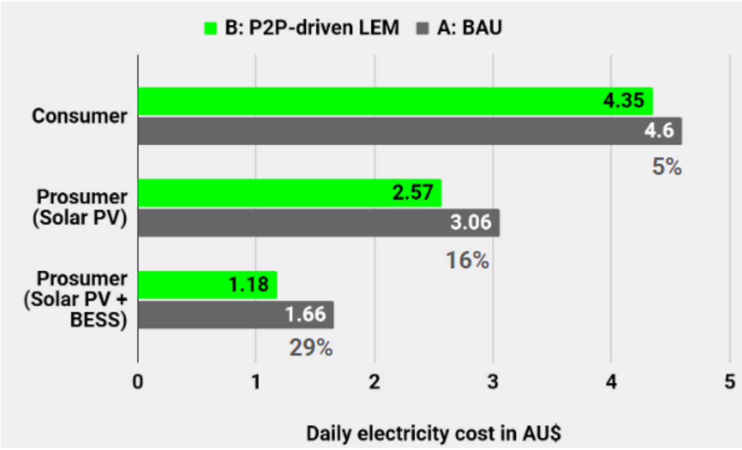


Figure 5: Participants electricity cost reduction

Drawing insights from Powerledgers' Australian case study on the Local Energy Market (LEM)[7], we observe a visual representation of the average electricity expenditures borne by electricity consumers, prosumers equipped with solar PV installations, and prosumers with solar PV and RBESSs in Figure 5. On average, engaging in P2P-empowered LEM results in a reduction of electricity costs by 5%, 16%, and 29% for consumers, prosumers with solar PV installations, and prosumers with solar PV and RBESSs, respectively.

In comparison to the BAU scenario. The reduction in electricity cost for prosumers is due to additional income received by P2P trading, using their own traded price and reduced grid buying/selling volume. Prosumers equipped with solar PVs and RBESSs experienced even lower electricity costs due to their increased self-sufficiency, participation in various time-of-use intervals for P2P trading, and a diminished reliance on grid transactions. This incentivizes prosumers to consider substantial investments in solar PVs and RBESSs to maximise their gains. Furthermore, consumers also reap moderate benefits by participating in the LEM platform without the need for investments in DERs.

[7] (PDF) Application of a Community Battery-Integrated Microgrid in a Blockchain-Based Local Energy Market Accommodating P2P Trading (researchgate.net).

2. Packaging up the electrical markets: Ancillary grid services

Ancillary services can be defined as any service not delivering electricity directly *to* the customer, but delivering electricity to the system to enable stability *for* the customer. Ancillary services are often seen as the [six different services defined by Drax in the UK] (as outlined below), but different grid networks may have different lists. Fundamentally, keeping the grid within its tight tolerances of voltage, frequency, and phase angle which determines reactive power all comes down to ancillary services.

FREQUENCY RESPONSE

All electricity on the network must run with a target frequency of 50Hz. Deviations beyond the secure limits of 49.5-50.5Hz can damage equipment or cause blackouts. Frequency response either increases or decreases the amount of overall power on the network on second by second basis so supply matches demand as closely as possible.

REACTIVE POWER

There are two types of power on the grid. active and reactive power. Active power is what powers lightbulbs. Reactive is the power that moves active power from power plant to bulb. The overall balance of reactive power on the system is managed and either topped up or absorbed in individual areas.

VOLTAGE MANAGEMENT

Adding reactive power or absorbing it has the effect of either increasing or decreasing overall voltage on the system. Great Britain's system runs at 400. 275 and 132 kilovolts (kV) and must stay within 5% of these figures at al times to remain stable.

INERTIA

At its simplest, inertia is an objects' natural tendency to continue doing what it has been doing when a force is applied. This resistance to change assists in dampening or slowing down large frequency changes. The spinning turbines of thermal and pumped storage power plants is calculated and referred to as system inertia on the grid, acting as a form of 'stored' energy that can smooth sudden changes in demand or generation.

RESERVE POWER

National Grid ESO keeps agreements with fast acting providers who can stand by to deliver a pre-agreed amount of power in the event there is an unforeseen change in demand or generation. Reserve power is not delivered as rapidly as frequency response but sees a greater volume of electricity pushed out onto the grid.

BLACK POWER

In the event of a total grid shut down, Black Start is the ability to start generating at a power station without the need for external grid electricity supplies and to then re-energise the rest of the network, in effect getting the country back online.

Figure 6: Six different ancillary services defined by Drax in the UK

Running ancillary services means having a close knowledge of the demands a customer base is likely to have on its network.

In recent years the cost of running ancillary services has grown substantially as shown in Figure 6. Drax reports that the changes in the use of electricity, coupled with the greater weather dependence of electricity means that there is a great need for ancillary services to keep the grid stable.

One way to understand ancillary services is about having reserves of electricity power on hand in the future. This future starts on the contingency side of things, measured in seconds with inertial energy and progresses to a more market-based and less contingent style of management with congestion and voltage management. These are all interventions that might happen within a week.

In addition to the markets described above, demand response is also becoming increasingly prevalent with many retailers now offering demand response packages. Demand response in the past often looked like an aluminium smelting works on hand and ready to shut down in short order, to balance the grid. The future might include industrial freezer food centres that have sufficient thermal inertia to allow a demand response operation. Current trends suggest that ordinary domestic consumers might well start making inroads into these previously purely industrial markets.

Demand response also becomes more important as the amount of electricity used during the day falls closer to what engineers call the "minimum demand threshold". That's the amount of electricity that must be consumed for the system to work properly. Having a guaranteed load will, in this eventuality, not just be a nice to have, it will be a critical system requirement. If this becomes another market that players of all sorts can participate in, when the system comes close to the threshold, the price of guaranteeing a certain amount of load will of course rise considerably.

With the rise of prosumers and domestic producers of electricity, it's possible that the ordinary consumer will become more involved with supplying ancillary services than ever before. This is a great opportunity for prosumers as ancillary services are more valuable and therefore better remunerated than standard power services.

In Figure 7, the dotted line inner shapes indicate the amount of energy that could be sourced for their respective markets from prosumers.

These are effectively all of the seven ancillary services bar the first two, inertia and regulation. Because the highest value ancillary services cost is more than 20,000 AU$/MW as shown in Figure 7 it's easy to see that such a market would be attractive to prosumers if they could get access to it.

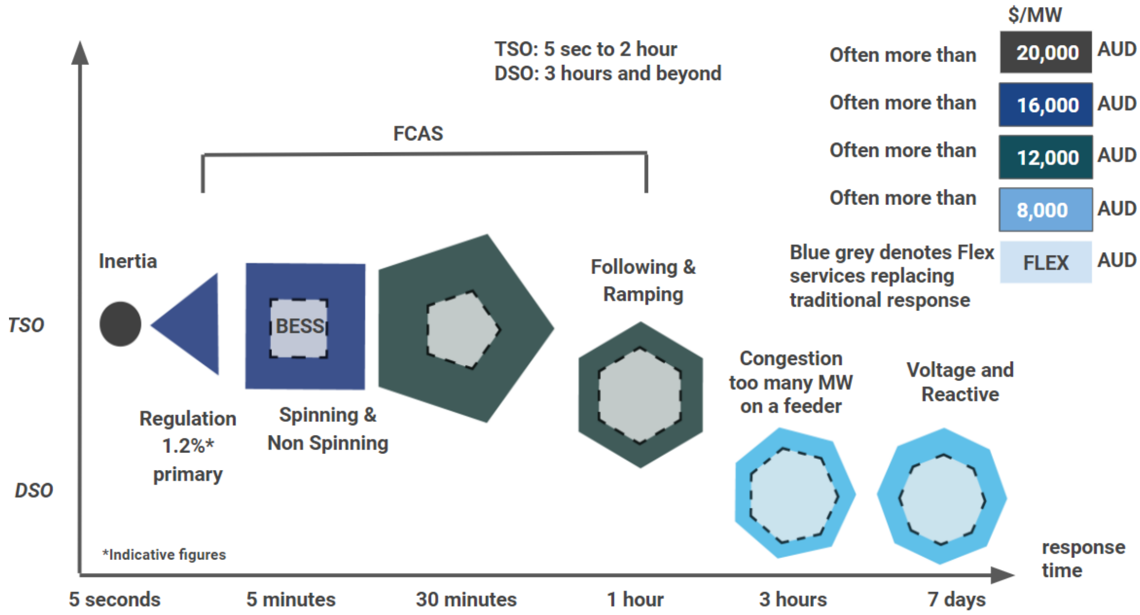


Figure 7: How flexibility helps ancillary services.

Of course, for a prosumer to participate in this market, they would have to guarantee a level of certainty. Their promised electricity would have to be available as contracted. The obvious way to achieve this would be with an assortment of penalty clauses, prudential bonds, and smart contracts.

A smart contract could be executed by a blockchain and would not be susceptible to delays or errors. Blockchain and smart contracts combined would suit the application of selling higher-value ancillary services. So if a prosumer defaulted on a promised (or contracted) quantity of electricity, the penalty would be immediate and non-negotiable. It could more than cover the cost of a peaker service or some demand response bought at short notice elsewhere. This typical market model of discounts for long-term contracts and penalties for defaults seems a feasible solution to ensure demand is always met.

At the moment there isn't a tested solution for the domestic player in the inertia market, which would of course have to be synthetic inertia. However, some experts seem confident that if you can define the problem of synthetic inertia, you can engineer the solution.

3. Centralised or decentralised responsibility?

In Chapter 1 we examined many problems renewable energy resources bring to the centralised paradigm in terms of spatial and temporal balancing. As a result, many commentators see just-in-time pricing and electrical trading as a feature of the future. Part of this will involve trading of what you might call “options” and “instruments”. In a P2P environment, electricity could be traded in units of 5 minutes between neighbours. At the end of a period, which could typically be a calendar month, all the trades would be netted off and a series of bills and payments made.

A number of questions arise from this vision of the future. If the future is P2P-based electrical production, what is the path that various electrical markets and systems will take to get there? What will be the scale of this design and what sort of entities will arise to enable this future to happen?

Talking to a senior electrical engineer from Western Australia, it was clear there were some more issues to consider. This source and his peers are clear there are temporal problems of the sort described in Chapter 1, but for him, the problem is exacerbated by what you might call the ‘stupidity’ of the batteries that we have at the moment. This engineer noted:

“We’re already getting grid problems, particularly around Easter, spring public holiday with nice sunny days when no one has got any heating or cooling on; there are high amounts of electricity coming out of the solar panels because they’re running at their most efficient. If one could put the surplus electricity into a battery and sell it to someone else that would be good. But one problem with batteries at the moment is that they’re not smart. You fill up your battery at around 3 o'clock in the afternoon, and if your battery capacity is large enough, in addition to servicing your own needs, you then pour all that excess into the grid, just at the wrong time. Clearly, the market has to be designed to make batteries more smart and bring some intelligence into the batteries. That would make everything work better.”

What is clearly required is a smart market that might even have a negative price for offloading electricity in this scenario after 3 o'clock in the afternoon, and a small positive price for before. Smart batteries would start learning to arbitrage and manage themselves so they become more of the solution, and potentially provide more profit as a result.

So how might that market begin to be established? One possibility on the route to a distributed energy network is the rise of aggregators and aggregation. Once aggregation is established, it’s possible there will be increasing competition amongst aggregators to become more local as they save on electricity transport costs. The rise of the community battery saves a lot of electricity transport.

In an Australian-style environment, you might typically have four players involved:

1. A generator/grid operator who owns the lines that connect houses to grids.

2. A retailer, supplying to a customer.
3. An aggregator buying from the customer, selling to the generator, possibly via the retailer.
4. A customer.

If the customer had a solar panel and inverter, or a battery that was not functioning accordingly, the generator would have to ensure the retailer liaises with the customer to fix the problem. It would be a complex four-way relationship and ultimately one agency or authority would have to be responsible for ensuring that the system worked.

This isn't as simple as it might seem.

Another scenario that is increasingly frequent: a large wind farm pumping out 100 MW of power has a bird fly into the cable. This creates a short and the wind farm is tripped out with either a voltage drop or a frequency drop as a likely consequence.

In the old days with a synchronous power plant down the road, the system would ride through it. But not so in an era of solar panels and inverters which may well sense trouble on the grid and trip themselves out to protect themselves, exacerbating the situation, and leading to a highly unstable grid.

This may not be a fault of the inverters, it may be due to incorrect installation or settings. It is clear that DER installation standards would need to be created and upheld by a single centralised authority.

However distributed and decentralised the power generation, there still needs to be a central authority setting standards to make sure everything behaves. There needs to be someone to carry the can.

3.1 Why India does it differently

India is recognising the value of DERs and is making rapid progress towards integrating DERs into the grid. Regulations permitting the sale of electricity between customers on a P2P basis are being enacted, and there are ongoing trials with variable pricing levels. However, there is less sensitivity and emphasis on a unitary organisation to 'carry the can' of responsibility for the whole of the grid's stability.

Perhaps what distinguishes India from countries like Australia and the UK, where there is a more conservative attitude towards the grid, is that "brownouts" are more regular occurrences. Outages due to electrical intolerance don't carry the same taboo or consequences. It will be interesting to see how the prosumer base in India picks up the notion of agile pricing and selling to one's neighbours. In India, there is also emergent aggregation, though the model is slightly different.

One other factor that makes India different is the cost of "brownouts". Electricity is mostly available there but the brownout management takes a lot of energy providers' budget (e.g. costly diesel generators need to be fired up). This high cost of emergency energy is a massive incentive for getting solar and wind to play their part.

4. Blockchain is the new standard of data interchange.

If we fast forward to an environment with widespread uptake of P2P and local energy markets, such as India, the question then arises of how to manage what could be the transactions of a million customers? And what are the implications of managing them in a centralised or a decentralised way, with blockchain or without?

In this new world where neighbours are selling to each and every other neighbour, there are a lot more transactions involved, compared with those required in centralised electricity markets.

If you consider, say, a 10-player network each of the prosumers can trade their electricity with 9 different neighbour connections (being everyone but themselves), and going around all possible connections, that would give 10 x 9 connections each way. This counts each way twice, assuming the buy/sell is just in one direction, so we divide by two. In general, this becomes:

$$n(n - 1)/2$$

Transactions would be for every five-minute interval of the day and the price may fluctuate throughout the day. In addition, there may be a range of packages that these electrical deals fall into, such as ‘mates rates’ for neighbours where there is a social bond or a rate for purely commercial relationships.

While such a level of data management isn’t outside the capabilities of a traditional database system, many engineers think that it would be better suited to a blockchain-based application.

There is no doubt that centralised databases have proved their worth over the years. Telecom models with usage of satellite time aboard yachts have shown how centralised billing systems can operate very efficiently. However, these systems were expensive and always positioned at high-spending users. Electricity consumption may be different altogether.

4.1 A simplified example

Let’s consider how that might work for a neighbourhood of 6 residents who are signed up to 3 different gentailers or retailers.

If we consider a simplified community example as shown in Table-1 where neighbours A through F exchange electricity while receiving additional, “top-up” power from the larger grid from Gentailers 1 through 3, the chart might look like this:

	A	B	C	D	E	F	Gentailer 1	Gentailer 2	Gentailer 3
A		1	-3	4	-1	7	83		
B			-2	3	-3	3		98	
C				2	-1	4		137	
D					1	3		50	
E						-1	43		
F									22

Table-1: A simplified example of a community where neighbours A through to F exchange electricity.

In this example A buys from B a single unit of value or quantity of electricity, and buys 3 units from C, i.e. sells 3 units of electricity over the same period of time. A buys most of their electricity from Gentailer 1, whereas B is signed up with Gentailer 2.

The Gentailers in this example, all consult a centralised authority of accountancy, let's call it the Central Regulatory Board who nets off all the numbers on this chart and provides the Gentailers with the final billing amounts. These amounts take into account all the neighbourhood P2P trading between A, B, C, D, E and F.

The Gentailers would have to be paid for their efforts and be audited by the Central Regulatory Board. This could be achieved by taking a percentage of the trades they process, as a fee. The funding for the Central Regulatory Board might be the state.

The same outcome could be achieved with a blockchain solution. The main difference is that instead of having a centralised authority in the Central Regulatory Board, the job of transactions and recording-keeping would be a distributed one. There could still be netting off, with the Gentailers responsible for billing via netting off, taking into account all Gentailers transactions with their respective customers.

One alternative here is that neighbours A through F are paid in some form of digital currency that represents the medium of exchange of electrical services, and a record of this is made in the blockchain. This is the Powerledger vision. This would mean that Gentailers wouldn’t have to do the job of effectively selling electricity that hadn’t originated from them and this may well simplify and streamline things.

4.2 Blockchain: Essential tool or technology for the sake of technology?

There is plenty of debate around whether you really need blockchain in situations such as those described in this paper, or whether it’s just a nice-to-have piece of high-powered technology that adds little in the way of functionality.

One analogy for the introduction of blockchain is the introduction of barcode technology to supermarkets in the 1970s. Barcodes were introduced in the ‘70s as a development of morse code and enabled a transition from a corner shop style of retail to the high volume, low margin style of supermarket we are all familiar with.

Crucial to their uptake was the increase in data input speeds that they enabled. From one item every two seconds by a skilled cashier, barcodes and laser scanners allowed a checkout flow rate of a hundred times what was previously achievable, and all by a relatively unskilled cashier. This made the new model of supermarket with lower pricing possible and paid for the cost of the new technology in a relatively short time.

What the barcode on a bag of sugar did was to encode not so much the price of the bag of sugar but the manufacturer, size, stock codes and other information. The database would then look up the price in real time and the transaction was completed. Suddenly the entire supply chain could be connected to the act of passing a sugar bag past a scanner and with it, a mass of data processing and “smartness” could follow. Crucially, keeping one's store stocked has been transformed from a visual inspection by the manager, to a data-oriented task by a computer system.

By analogy, what will become important in the future isn’t just the amount of electricity transacted between neighbours A and C, for example. What will also be important is the time of transaction, the certificate of greenness, the origin, the destination and so on, a host of attributes that will become increasingly important in the future.

4.3 Separating attributes from the energy

The ability to separate the energy attributes from the energy itself and sell those attributes into a market has given rise to a whole industry of green-oriented energy based on GOs (guarantees of origin) EACs (energy attribute certificates) or RECs.

The premise of all of these is that you can separate the attribute from the energy itself and trade them as different items, with their own markets.

This industry will play an important role in helping the energy transition take place. By creating revenue streams for solar panel owners, and wind farm investors, RECs can help speed up the adoption of renewables.

However, like the carbon credit systems from twenty years ago, there is the possibility of fraud and misuse and these issues are discussed more fully in Chapter 6

But if certification systems are going to be reliable and trustworthy, the onus on creating traceable electricity units that are secure against all manner of fraud and bad actors, becomes of paramount importance.

Whether a centralised classical database is up to this and can resist all the cyber attacks on it is a question still being debated.

4.4 Blockchain as the standard of data interchange

To some extent, the answer to the question of whether blockchain is a vital new component or piece of electronic solution looking for a problem, depends on who you ask.

Ask someone over the age of 50 and they see the latter, a solution looking for a problem. But ask an engineer in their 20s, 30s or 40s and you get a different answer.

A senior energy expert from India is very clear about how blockchain will play a crucial role in the future of grid solutions:
"It's important to see blockchain as a protocol. Just as SMTP, POP3, IMAP, https and EDI became standards that enabled engineers to use out-of-the-box solutions and save huge amounts of bespoke designing and making things that weren't compatible with other things. Inevitably, we will see blockchain become a standard in the same way."

Certainly, if blockchain does become a standard, there's no shortage of applications that could be conceived of in the future. Whether they are tracing, recording, optimising, authenticating or reconciling energy, these functions are already being used and paid for.

Why wouldn't you want a format to enable more of them to be created and installed easily?

In some way, engineers have always used the latest materials of their time and deployed them across a slew of applications.

Just as Victorian engineers like Isambard Kingdom Brunel made cast iron and steel their choice of material for their works, which ranged from steamboats to bridges, buildings and railways, they were using a material of their time that lent itself to a host of applications. When carbon fibre came along a century later it too became a standard across a gamut of applications that replaced many of the solutions before it.

4.5 Blockchain friction and auditability

When any organisation is required to keep accounts for its membership it generally has to be audited like a financial institution.

For example, a phone company is not normally in the business of creating mortgages, lending money or other forms of financial instruments, but it still has to deal with its customers' accounts. For this reason, it has to create an auditable report of everything it does and this takes both time and money.

In the days when phone companies were sending bills that were hundreds of pounds, having to create auditable reports made financial sense, but if you transpose the idea to a decentralised network of peers exchanging electricity this notion breaks down.

If you have a million customers with a set of transactions between them the question arises as to which centralised authority wants to have the duty of accounting for all this activity and sending the appropriate bills?

If the energy supplier does not make a margin on the power traded between customers, why would they want to invest time, effort and the risk of being audited to manage everyone's billing systems?

This is the point where traditional database systems (DBS) fall down. It may well be that the technology of a traditional database has been established and can even work effectively with a large number of accounts, but what entity would own it, pay for it and operate it?

If each transaction costs the management team say $0.001 to process and audit, there could very well be 10^{12} different transactions. This means the cost could significantly and likely proportionally exceed. A decentralised system, where the incentive to maintain the network lies with the stakeholders and network participants would be much more appealing in this scenario. For this reason, many grid experts looking to the future are visualising a blockchain basis for the technology.

We can sum up the issues for centralised databases with three drawbacks: error and fraud, friction and the onus on accountability.

5. Towards the future of the grid

Up until now the complex ancillary markets, financial derivatives and other instruments have played a decisive role in supporting grid operations. Industrial demand response industries like aluminium smelting have played their part too, and all of these have been relatively separate from the consumer and prosumer. But what is both foreseeable and exciting is the convergence of prosumer markets with professional ancillary markets.

As discussed in Chapter 2 it's perfectly possible that savvy prosumers will want a piece of the more lucrative ancillary markets.

This may well happen through intermediaries or aggregators. We have also imagined a highly evolved future market, where machines can book slots for bigger discounts provided they honour them. Figure 8 shows a future dishwasher application that would book an electricity slot from the forward facing market.

Figure 8 : A future dishwasher application would book an electricity slot from the forward market and result in a penalty for default of not providing the energy.

Figure 9 presents the routine weekly updates provided by the Australian Energy Regulator (AER). However, this particular figure offers a condensed overview of significant occurrences spanning the last two years. Within Figure 8, the AER has diligently monitored and documented noteworthy price surges throughout the National Energy Market.

These would effectively integrate forward-facing markets of the 30 minutes to 7 days described in Figure 10 and make them available to prosumers. Weather data along with data such as bank holidays and other economic data would all be material to establishing a price curve.

The discrete markets may in time blend into a continuous market with prosumers responsible for much of the volume of it.

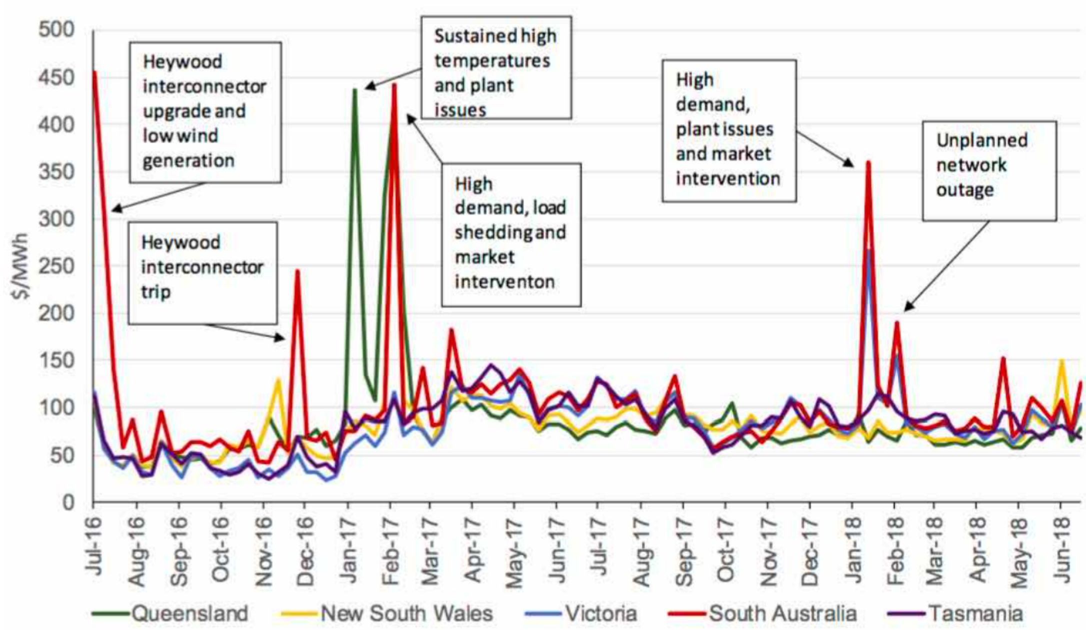


Figure 9: This is an example of weekly average spot prices in the wholesale market in Australia. We could see the development of a continuous forward market where traders including prosumers and their devices can specify any unit of energy at any time in the future. In such a local market prices will follow a similar pattern to the wholesale market[8].

Meanwhile, as well as a long-term electrical price there would also be a demand response price. Such a market would need to consider a penalty price for defaulting on a contract to provide either of the previously mentioned. As these mature, penalties for default would have to be significant to act as a deterrent, instant, easy and efficient to enforce. Such defaults could happen if a prosumer/consumer is unable to fulfil their obligations, if the transactions become unmanageable or also if they get hacked.

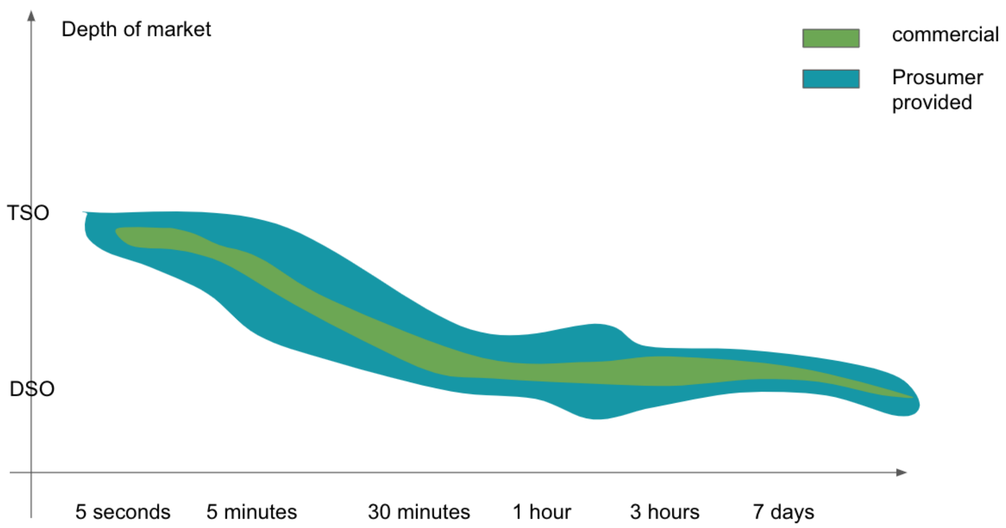


Figure 10: The discrete-time bands may merge into a continuous one as more players join in and grid services will not only be provided by large TSOs and generators but also by DSOs and smaller prosumers/consumers.

[8] https://reneweconomy.com.au/graph-day-really-causes-biggest-price-spikes-32400/

All of this suggests a secure blockchain solution as with so many transactions between players would be better than a traditional DBS.

Blockchain is a better solution for secure transactions between players than a traditional database.

5.1 Large numbers of transactions could attract opportunities for fraud

Perhaps one analogous fraud in recent times that is relevant here is the LIBOR scandal where a group of bankers manipulated the LIBOR the London interbanking rate. Although the percentages were very slim and barely noticeable, the sheer volume of transactions involved meant that large amounts of money could be defrauded. With n(n-1)/2 transaction sets for n players the large number of transactions could lead to similar types of skimming off money. Hence blockchain would be a guard against such attacks.

Certainly, as cyberattacks become an almost everyday occurrence, the system data security benefits of blockchain become significant. So too will be the ability to create a digital inventory (DI) of participating assets with all their certificates that qualify for relevant attributes.

In short, in this new world, a host of attributes can become integrated into one data system, just as happened with barcodes and our bag of sugar in 1970.

6. Attributes, certificates and fighting misuse

In Chapter 4 we introduced the notion that one could separate the energy's attributes from the energy itself and sell these to a market or a buyer of green energy attributes. This effectively creates a revenue stream that encourages investment in renewables.

As shown in Figure 11, the markets around RECs, EACs and GOs have increased substantially over the last few years since they were introduced and have no doubt contributed to the sum of all available renewable resources in many parts of the world.

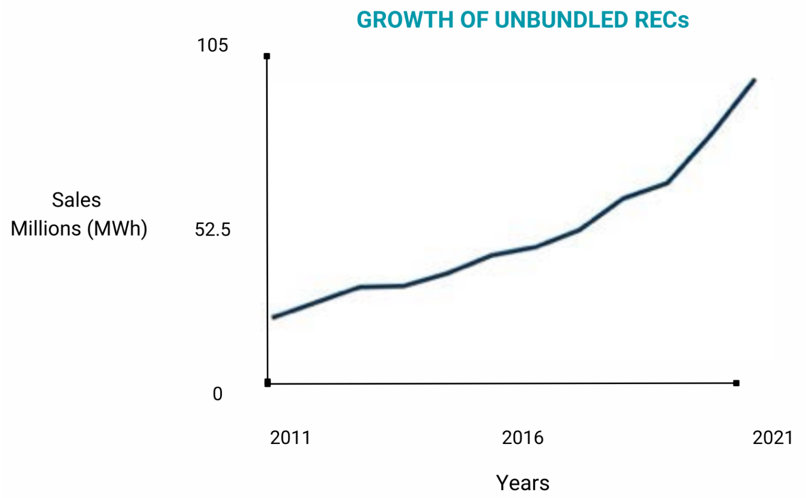


Figure 11: The growth of certificates

[NREL Status and Trends in the Voluntary Green Market (2021 Market Data)]

Whether these resources are now stationed at the right place and contributing at the right time will be discussed later.

But with this growing market has come a certain amount of abuse and misuse of the certifications scheme, as a form of greenwashing.

Greenwashing is a widespread problem today and occurs when companies try to appear environmentally friendly, without actually changing their harmful behaviours. For example, a company might advertise its purchase of carbon credits and engage in "double counting," where it claims the environmental attributes of the renewable energy it produces for its own clean energy goals but then sells the RECs that contain those same attributes to other companies, effectively inflating their positive impact.

Here's how the EAC accounting process can fail: Company A and Company B claim to be 100% renewable powered. Company A may own an on-site solar array that generates electricity but they have sold the energy attributes (i.e., RECs) to finance their solar array. Company B purchases the RECs that were produced - from Company A's solar system. While both organisations are claiming to be 100% green powered, only Company B has a legitimate claim, since they contractually own the RECs associated with the system solar power production and can say they are solar powered.

Notable companies accused of greenwashing include Volkswagen AG, BP, Mitsubishi Motors Australia, Woolworths, Tlou Energy, and others.

The solution to this issue is rigorous tracking and tracing of the energy and its original certification so that such abuses don't occur. For this, blockchain is ideal.

It's not the first time that new technology has made it easier to reduce fraud. Back to the barcode example from the 1970s, when the stock became barcoded, it became harder to steal items and sell them illegally because there was now a wider net of accounting and so fewer items 'fell off the back of a lorry.'

One other way tighter tracking could improve the beneficial effect of certificates is by making them more time and place-specific.

Increasingly it's becoming clear that certificates need to reflect a granular picture of the electricity they're representing. If a kilowatt hour of renewable energy created during the day gives rise to a certificate that is used to offset a kilowatt hour consumed in the evening and from a fossil source, there's a problematic mismatch between them. A much more effective accounting solution is to require that certificates be used by a consumer using fossil power in a similar place and at a similar time to when the renewable certificate is produced so that the system is incentivised into a more sustainable place. For example, by encouraging the purchase of a battery that would store the renewable energy produced during the day and then be used in the evening when only fossil source power supplies may be available.

Such issues all point towards a more complex, more nuanced and information-rich set of markets that need a blockchain-style technology to underpin them.

6.1 Environmental Commodity Solutions

In regions such as Europe and North America, there are multiple environmental commodity registries with limited connectivity to each other. This means customers and generators often require separate registry accounts in each region they wish to trade or retire RECs and carbon credits.

Additionally, in both regulatory and voluntary markets, targets are set and measured annually, so there is a final annual audit stage for all retired RECs and carbon credits to check if the targets have been met. This process traditionally faces issues like double counting, manual operational errors, system inefficiencies, market inefficiencies, duplicated participation processes & costs, and a lack of transparency.

As shown in Figure 12, blockchain technology presents a compelling solution for these issues. It is decentralised and immutable, making it an ideal foundation for a REC or a carbon credit registry and marketplace. A blockchain-based solution can remove the manual over-the-counter processes, enabling instantaneous ownership transfer and settlement, thereby eliminating counterparty risk. It also creates an immutable audit trail of ownership from issuance to retirement.

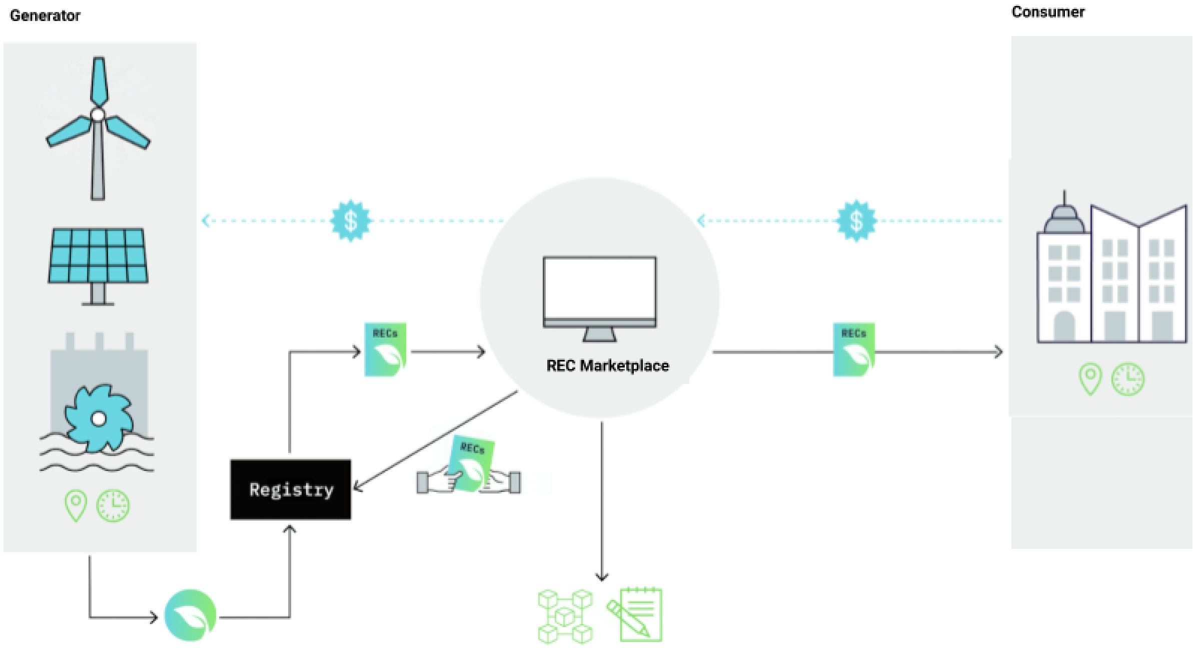


Figure 12: Interaction with generators, EAC registries, marketplace and consumers, authors

The tokenization of RECs and carbon credits through blockchain could also offer significant advantages. It enables fractional ownership, which allows smaller investors to participate in the renewable energy and carbon offset markets. Coupled with blockchain's transparency, this ensures the traceability and authenticity of RECs and carbon credits, reducing the risk of fraud, double claims and greenwashing.

7. Conclusion

In this report, a global perspective is presented with examples spanning across different regions, including California, the USA, Germany, India, and Australia. These examples illustrate the challenges and opportunities associated with integrating variable renewable resources (VREs) into the grid. The report emphasises the common issues of intermittency, spatial distribution, and the emerging challenge of inertia in the context of increased VRE usage. Furthermore, it highlights the effectiveness of Local Energy Markets (LEM) and peer-to-peer (P2P) trading in mitigating these challenges, reducing electricity costs, and enhancing grid stability. Ancillary services, vital for grid stability, are also discussed, with a focus on the growing costs associated with their provision in the UK.

The debate about decentralising the finance behind the grid may have already been settled. Just as every generation of engineers uses the best and or the most widely adopted tools available to them, it's likely that blockchain will have won over the hearts and minds of the next generation of engineers who will be designing the distributed grid. Just as all of us set up an IMAP or POP3 protocol on our smartphones without giving it a second thought, it's possible blockchain reaches that tipping point of a standard protocol in all our lives. In other words, the next generation of engineers has already alighted on blockchain as the standard tool in the toolbox.

With that blockchain future, it's possible to see a host of applications that meet the emergent needs around the new grid.

In the future we may see a convergence of ancillary and prosumer markets, either aggregated by intermediaries or not. This would represent the evolution of a new way to create a stable grid leveraging the prosumer market. The existing market designs would be supplementary and in competition with these newcomer prosumer markets. The prosumer markets would create revenue streams that would encourage the right investment in the right way and the right place for use at the right times.

While our grids ponder investments to solve their immediate capacity issues, such a paradigm shift might be the solution to these and many other problems.

Appendix

The Disadvantages of Centralised Systems

Centralised systems have been a fundamental part of our society for centuries. From government and finance to healthcare and transportation, we rely on centralised systems to provide us with the goods and services we need to live our lives. However, as our society becomes more complex and interconnected, the disadvantages of centralised systems are becoming increasingly apparent.

1. ***Single point of failure***

Centralised systems rely on a single point of control, which means that if that point fails, the entire system can come crashing down. This is because all of the power and control is concentrated in one central location, making it vulnerable to system failures and disruptions.

For example, if a bank's centralised system experiences a failure, all of its customers may be unable to access their funds, causing widespread panic and chaos. Similarly, if a government's centralised system for managing elections is compromised, it can undermine the legitimacy of the entire democratic process.

2. ***Lack of transparency***

Centralised systems can be opaque, with the decision-making processes and algorithms used to govern them being hidden from public view. This can create a lack of trust and accountability, as users are not able to fully understand or participate in the system.

For example, if a social media platform's centralised algorithm is biased against certain users or content, it can be difficult for users to challenge or understand the decisions being made. This can lead to a sense of disenfranchisement and disempowerment among users.

3. ***Vulnerability to attack***

Centralised systems are often more vulnerable to security breaches and hacking attempts than decentralised systems, as all the sensitive data and infrastructure are located in one place. This makes centralised systems a prime target for malicious actors who seek to steal data, disrupt operations, or cause chaos.

For example, if a hospital's centralised system for managing patient records is hacked, it can compromise the privacy and security of thousands of patients. Similarly, if a transportation system's centralised control centre is compromised, it can cause widespread disruption and danger.

4. ***Limited scalability***

Centralised systems can struggle to keep up with demand as they grow in size and complexity. This can lead to long wait times, slow processing speeds, and reduced efficiency.

For example, if a public transportation system's centralised control centre becomes overwhelmed with demand during rush hour, it can lead to delays and frustration for passengers. Similarly, if a government's centralised system for processing tax returns becomes overwhelmed during tax season, it can cause delays and backlogs.

5. ***Lack of user control***

In a centralised system, users have limited control over their own data and how it is used. This can lead to privacy concerns and a sense of disempowerment among users.

For example, if a social media platform's centralised system collects and uses user data without their knowledge or consent, it can undermine users' privacy and trust in the platform. Similarly, if a government's centralised system for collecting and storing citizen data is used for nefarious purposes, it can undermine citizens' trust in their government.

Overall, the disadvantages of centralised systems highlight the need for more decentralised and distributed alternatives that can offer greater security, transparency, scalability, and user control. As our society becomes more complex and interconnected, it is increasingly important to rethink our reliance on centralised systems and explore new, more resilient models of organisation and governance.

6. ***Poor allocation of resources***

Highly centralised economies, especially ones governed in an undemocratic way have often created famines reflecting a failure to adapt resources for the needs of the society.

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