Micro Compressed Air-Energy Storage and Thermal-Energy Storage

An energy storage solution across short, medium, and long duration energy

The energy storage of tomorrow will
require an entirely new service level.
mCAES/TES is an answer

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INTRODUCTION

MDI, a European technology innovation firm, and long term partner Air Future Group (AFG), an Australasian commercialisation firm, are now poised to consolidate their efforts and embark on mass commercialisation. The joint focus is to rollout an Australasian showcase highlighting MDI's ground-breaking technology applications across the vast markets established by AFG across Australia, New Zealand, and the Pacific Islands, followed by global replication.

> *"The implications of this for the future of decentralised scaled and longer duration storage are nothing short of spectacular, thereby managing energy delivery completely flexibly and affordably"*

Over the course of more than a decade, MDI has diligently developed their globally unique and revolutionary energy storage technology mCAES (micro compressed air energy storage). On completion of the final stage of thermal optimisation via thermal energy storage (mCAES/TES), this single system will be unique in its provision of trigeneration for energy users, and the multiple affordability, efficiency, and energy density capable of being provided.

What is most spectacular is the mobile mCAES/TES system is completely modular, with the system's storage power capacity and its energy delivery are asynchronous (decoupled), and both are completely scalable delivering capacity and duration as required (as designed), whilst both remaining flexible during that process. The development of the mCAES technology has been likened to Tesla's pioneering work on batteries, which initially focused on transportation applications before expanding into energy storage solutions. MDI's journey, akin to this historical parallel, originally designed the compressed air "battery" for innovative lightweight composite-material vehicles. MDI collaborated with various companies during their technology development including the likes of Tata Motors, Veolia, and KLM Airlines.

Whilst the transport potential is impressive, it is stressed these were development projects and focused on development. Now the focus is on mass commercialisation and the immediate priority is on energy storage; initially across the markets in Australasia with local manufacture. To that end MDI applied further technology to create a fully flexible and modular storage system, and commenced creating the integrated compressed and thermal energy storage. They inaugurated their state-of-the-art energy Air Energy Laboratory facility, equipped with solar generation and flexible storage capabilities.

In parallel AFG explored the developments both local in Australasia and globally in energy networks' modernisation, energy storage developments, and the commercial and social swings and roundabouts as politically and ecologically climate pressure escalated on abatement of greenhouse gases. Clearly there was a somewhat parallel universe evolving in centralised and decentralised energy, and in short and long duration storage.

> *"The concept of an energy storage cloud with advanced digital controls is fast becoming a reality."*

What AFG envisaged however was not simply the dichotomy between short and long duration, but in reality that there was a third area of mid duration – and therein was a gap that could have far reaching implications. Herein we present the philosophy around that proposition, the execution of solutions, and the implications of ignoring them.

EXECUTIVE SUMMARY

In an era marked by an inexorable shift from fossil fuels to renewable energy generation, we confront a monumental transitional challenge. It is balancing the availability and affordability of energy from traditional sources while the new sources reach scale. Failure to do so could lead to social and economic turmoil and poses a perplexing dilemma for policymakers. But the challenges are more considerable than these obvious ones.

An electrified world is not automatically a decarbonised one, as full decarbonisation can only happen once you are fully electrified. Whilst there is any reliance on fossil fuels there are going to be embedded carbons, we are incurring a carbon debt, and that debt needs amortisation. For example we currently produce new carbon pollution in producing electric vehicles or solar panels. So from a planet perspective they start in debt. Only via their operation, which is saving carbon, are amortising that debt.

So considered in isolation, the more we can use the solar and EVs relative to our previous usage of fossil fuel or internal combustions engines, the more we head into the black for these products. Don't compare to the old dirty world, but to the 2030 & 2050 targets including net zero. Note: In this paper we ignore hydrogen storage and its many carbon colour codes, or carbon capture and storage, or nuclear fusion, or the commendable effort of planting trees.

Now here are the three problems we face in this scenario of energy transition:

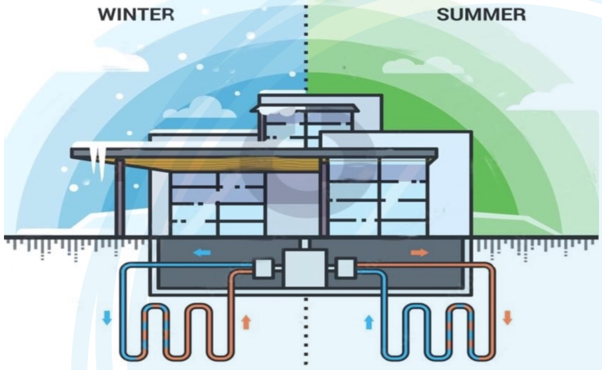
- It is estimated that to electrify the world we need at least 300% the amount of todays energy (ignoring organic growth). So the challenge is actually far greater.
- It is always better to tackle an acknowledged problem than a denied one. And a transition of such monumental proportional challenges is going to create denials (which is already the case).
- There is a sociological shift taking place towards independence and control (taking matters into one's own hands), facilitated by the software and digital revolutions. Energy modernisation will also embrace it.

What do we do? Well, there are no technical constraints in growing solar and wind generation to massive scale. But there are three major constraints:

- Solar & wind generation is intermittent. That problem is not just about the effect of renewables into the grid, it's also about renewables off the grid, due to the constraint above re their utility. This starts to become very evident when one is seeking scale, duration, resilience, reliability and so forth.
- There is a manyfold challenge in moving from a centralised controlled grid to a decentralised uncontrolled grid.
- Harnessing intermittency via storage can largely address these first two points, however there are technology and network challenges with storage that have not yet been addressed, such as long duration.

> *The main focus in this paper is simply how mCAES/TES can be a solution for scaling up decentralised energy.*

In this paper we seek to take solutions to these challenges to a new level via new concepts and technology and processes to execute them. For example we will address the current middle duration storage gap in decentralisation, and why long duration doesn't address that. And how integration of short, medium and long duration can lead to an energy storage cloud, and how "justice for all" can become a climate reality, how decentralisation can challenge client ownership, and how distributed energy resources can be financed on a securitised (pooled) basis.



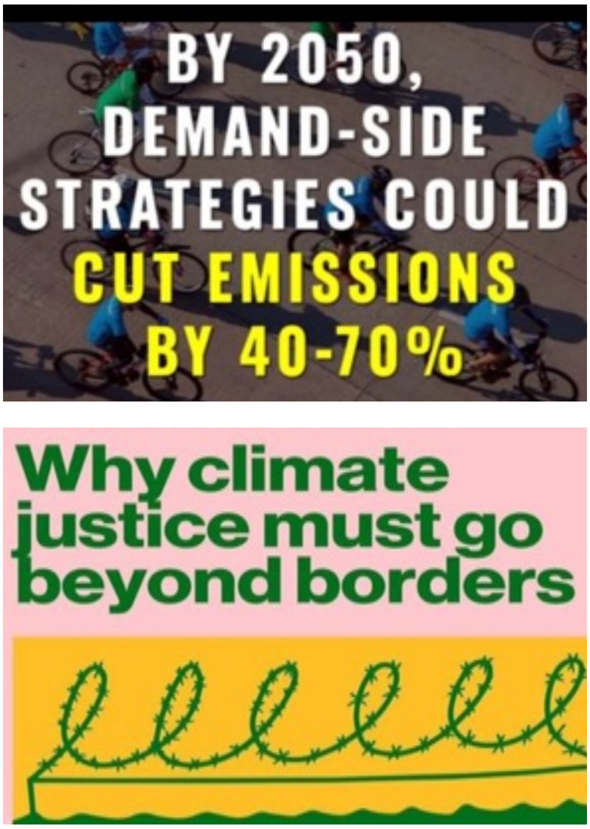
Above: With extreme weather everywhere, what is needed is new technology to provide resilience.

EXECUTIVE SUMMARY CONTINUED

This predicament not only complicates the allocation of resources but also hinders progress toward achieving the global targets set for 2030 and 2050. This paper introduces a technology that offers a timely and cost-effective contribution to scaling renewable energy production.

> *“Balancing the availability and affordability of energy from traditional sources while the new sources reach scale is of paramount importance.”*

The integration of Micro Compressed Air Energy Storage (mCAES) and Thermal Energy Storage (TES) represents a ground-breaking innovative solution. This paper will not only elucidate the technology but, more importantly, bridge the gap between the aforementioned challenges and the potential for widespread impact.



Above: Decentralised demand management can be the answers to COP & IPCC requirement for climate equality.

We achieve this through five key areas of focus making up the topics herein:

1. Modernising Energy Storage

This topic highlights the pressing need for modernising energy storage, particularly as the supply for renewable energy sources and thereby effective energy storage solutions increases. It sets the stage for discussing how mCAES/TES technology can contribute to this transition, highlighting the centralised-decentralised differences.

2. Decentralised storage differentiators

We now address the challenges faced in energy storage and the characteristics that distinguish storage types and why they count. We address the critical aspects of storage scale, duration, efficacy, and cost when matching storage to applications This topic introduces the mCAES/TES solution as a technology designed to address these challenges.

3. mCAES/TES decentralised technology

In section 3 we delve into the innovation behind mCAES/TES technology, explaining its modular components, capacity, and flexibility in its applications. It provides insights into the technology’s readiness and its potential in both mobile and middle-duration energy storage. It addresses the completed and completing thermal roles.

4. mCAES/TES decentralised markets

Here the discussion shifts to the evolving markets for storage and hence mCAES/TES, including a breakdown of storage markets and the capacity and duration aspects of these markets. It differentiates between direct and indirect customers and provides insights into the decentralised user markets. It highlights the three levels of storage durations for energy storage modernisation and their interactions - short, medium and long are addressed.

5. Commercialising Australasia & global replication

The final topic addresses the team and the partnership behind the Australasian showcase and regional projects in bringing mCAES/TES technology to fruition. It introduces MDI and Air Future as key organisations driving this effort, and explains the distributed micro manufacture readiness. It paves the way for investment and partnership to progress the potential in discrete parallel steps.

1. MODERNISING ENERGY STORAGE

In its capacity as one of the largest contributors to greenhouse gas emissions, the energy industry occupies a central role in the global drive toward electrification and the decarbonisation of both energy supply and consumption. It also plays a pivotal part in influencing emissions across other sectors, including transportation. This transformation necessitates the widespread adoption of renewable energy sources, coupled with the reduction of emissions embedded within the energy network and the operational emissions in various industries in providing services.

> *“Never before have we seen a situation where energy customers and users can basically provide their own energy independent of centralised corporations and governments determining the pricing and availability”*

The impact of energy storage

The familiar energy grid, as we have known it, is poised for a comprehensive modernisation. This overhaul is essential to accommodate the predominantly intermittent nature of renewable energy sources and to phase out the legacy grid that relies on stable fossil fuel-based generation and requires ecologically unfriendly transmission.

Facilitating this transition both across the energy sector and its interrelated industries hinges on the widespread implementation of energy storage. In its practical application this includes short-duration storage (ideal for high cycling and rapid response), medium-duration storage (to support decentralised generation and off-grid demand), and long-duration storage for weeks and months of energy storage for the grid or other networks.

> *The comparisons of energy storage are application specific not laboratory or component specific*

Now a key point in the early days of energy storage – energy storage is application dependent. Compare the wrong characteristics and you’ll get the wrong outcome. Consider randomly some of the storage characteristics below.

Decarbonise:	enables adding more renewables
Efficiency:	makes renewables more effective
Intermittency:	counters solar and wind variations
Price time shift:	shift to storage when grid expensive
Reliability:	assure adequate electricity at peak time
Efficacy:	provide backup when supply is halted
Affordability:	make renewables energy less expensive
Economical scale:	enable effectiveness for microgrids
Flexibility:	modularity & flexibility for tailoring
Duration:	provide energy for longer periods
Cycling:	the fill-empty cycle times
Fast response:	how quickly storage can discharge
Safety:	provide a level of security
RTE:	provide storage efficiently needing less input
Efficacy:	all factors affecting the suitability for an application
LCOS:	lifetime cost of the storage into a single comparison
Cross services:	multiple services from the storage system
Capex:	Cost to acquire or construct the storage
Opex:	comparative cost of operating the storage
Density:	energy density or space per energy
Discharge & lifecycle:	operation in situ
Modularity:	flexible catering to applications

Choosing any benchmark and comparing lithium ion batteries, hydrogen fuel cells, pumped storage hydro, compressed air, nuclear, geothermal, and so forth by criteria that are not applications specific will likely give different answers every time.

For example lithium ion batteries have high round trip efficiency, high energy density, fast response, and short cycle time. But they also have characteristics that make them totally unsuitable for many storage applications.

Centralised big batteries can facilitate more renewables but are only short duration

1.1 Centralised utility level

For decades, the energy industry has predominantly relied on centralised power generation systems, exemplified by coal and natural gas power plants, which have served as the cornerstone of our energy infrastructure. This approach entails the establishment of a fixed base load network with the flexibility to accommodate peak demands via gas peaker plants. The quantity and quality of electricity is managed by authorities with governing power, such as AEMO and the NEM.

The integration of renewable energy into the grid is a global phenomenon, yet traditional energy sources continue to play a significant role in many regions. Country by country policies are still heavily influenced by considerations of energy capacity and consumer pricing, affecting the rate of take up of renewables.

The other factor affecting utility level centralised renewables take up is their intermittency and the network disruption that causes.

Storage technologies can assist in addressing this challenge, but existing battery storage solutions are suitable for short-duration applications and are not suitable for longer durations. There is now a growing awareness of the need for longer duration storage, with examples including pumped storage hydro, hydrogen, large scale compressed air energy, and so forth. There is also the need for shorter duration but fast response and short cycle time storage to facilitate the take up of renewables, and here we see the increase in centralised mega batteries,

Often long duration energy storage (LDES) involve large-scale civil engineering constructions, and these infrastructure level projects entail significant capital costs, which are a primary contributor to their Levelised Cost of Storage (LCOS), though over time their LCOS tends to be the most economical option. Generally LDES will deliver their stored energy via traditional transmission, delivery, and retail, which adds cost and climate impact.

> *“If centralised storage is paramount to utility generation, the network formula changes to generation – storage – transmission – distribution – retail. This needs to fit into the energy network modernisation?”*

Decentralised microgrids such as Ikea's microgrid impact both demand mangement & grid support

1.2 Decentralised user level

The renewable energy era has given rise to generation, for example solar and wind, to be provided not only centrally but decentrally at scale, from kW to MW to GW on an aggregated basis. Hence this new era is no longer dependent on centralised utility energy generation, and similar characteristics apply decentrally, such as intermittency. And that requires energy storage to optimise either user energy or grid feed.

Presently, whether in Australia or globally, there are dissatisfactions with both the pricing and services provided by the energy network as it transitions toward renewables. This is in part driving a remarkable surge in decentralised non-utility BTM (behind-the-meter) rooftop solar installations, and increasingly commercial rooftop solar.

> *"Now the potential here is obvious - create decentralised energy scale and sharing of distributed energy resources"*

Consider some of the decentralisation opportunities, momentarily in absence of any hurdles:

- Wind and solar have complimentary intermittency
- Via microgrids and distributed energy resources management systems, energy can be shared
- Distributed energy resources can also be aggregated leading to virtual power plants
- Resources can be scaled, such as solar, wind, or storage farms
- Developments can be financed to remove front end capital costs

As you would expect, both across centralised and decentralised energy modernisation there are hurdles. Our focus is on the role that mCAES/TES can contribute to energy storage modernisation, and why this is unique.

Storage goes with generation, and the extent of decentralised solar & wind means storage goes decentral. But it needs scale

2. DECENTRALISED STORAGE DIFFERENTIATORS

While centralisation and decentralisation may initially appear to compete for customers, there is potential (rather desire) for a synergistic coexistence, as each provides different assets and applications. Energy storage transcends both centralised and decentralised generation and the mere capacity enhancement for intermittent generation.

It also serves to improve generation efficiency, reducing the need for excess generation and accelerating the amortisation of costs and embedded carbon. Remember electrification requires a huge increase in energy. Ultimately, this leads to more affordable energy and swifter access to equitable energy distribution.

A pivotal transformation arises when storage reaches scale and aggregation across short to medium to long duration timeframes. At this point, decentralised energy systems become akin to massive power plants, albeit with notable distinctions.

Due to the lag in commercialising storage innovation across duration and capacities, combined with the growing experience in centralised and decentralised energy, it is worth reflecting on some key storage modernisations.

2.1 Location near generation & customers

A first defining characteristic is that most traditional storage today is discrete rather than modular. Meaning you can add whole components, but not parts. So you can buy a battery but not add a cell. It is fixed kW/kWh. The second defining characteristic is the nature of the storage's charge and discharge cycles. These factors will contribute to duration.

Traditionally storage and its capacity and duration have not been front of mind, but with renewables it is critical. However as renewables take over, and energy generation triples, storage becomes the holy grail for energy network modernisation – both centrally and decentrally. This is well understood and accepted.

> *"In the wake of the famous Castrol marketing slogan "oils ain't oils", we can now propose a new age one "storage ain't storage"*

As per the earlier storage characteristics list, different storages have different characteristics ad therefore are better suited to particular applications. One of those characteristics is storage duration. In the last few years the significance of long duration storage has rocketed up the priority list, and $100 millions and $billions have gone into singular projects. Predominantly these are civil engineering infrastructure scale projects.

And yes, that means they are centralised utility type projects requiring the traditional generation – storage – transmission – distribution – retail model in most cases. It also means they are location specific.

> *"Now we have a dilemma. We have short duration and long duration storage. But decentralised storage is mid duration"*

It is mid duration because of its decentralised generation, its economics, its resilience requirements, and simply because it fits in with the decentralised social models of controlling community energy in the community. For example, if Florida State in the USA experiences a typhoon that brings down the power, it's not much use having long duration storage in another State.

At a smaller scale in Australia it's not much use having the Snowy pumped hydro scheme if there is a cyclone in Darwin. So the new modernised energy network and storage requires three levels of storage. But these are not discrete – rather they overlap.

2.2 Modularised storage, scale & duration

At this point it is worth stressing that it's digital technology that holds the potential to reshape the energy industry as we know it, especially for decentralisation. Within this context, solar panels, wind, energy storage, smart metering, are collectively referred to as Distributed Energy Resources (DERs). These DERs can be digitally coordinated and controlled via a DERMS (Distributed Energy Resources Management System).

DERs can form part of an isolated system as BTM (Behind the Meter), or exist as part of a grid network system as FTM (front of the meter). The term "bidirectional" refers to whether the system can both draw energy from and supply energy to the utility grid. "Off-grid" signifies that the system operates in isolation from the grid. These concepts are equally applicable to commercial buildings and industrial sites, which can be considered as isolated users.

Isolated users, once integrally connected and coordinated, give rise to microgrids. These microgrids can be grid-connected or operate independently. When aggregated, the kilowatts of power from these microgrids begin to take on the scale of megawatts, effectively transforming the microgrid into a Virtual Power Plant (VPP). VPPs possess the capacity to bring scale to DERs by their integration. That may be done digitally, such as combining rooftops, or physically, as in community solar, wind, or storage centres or farms.

> *"So with more and more integration via commercial, digital and locational energy asset and user coordination, so do we add more and more scale, and need greater storage capacity and duration"*

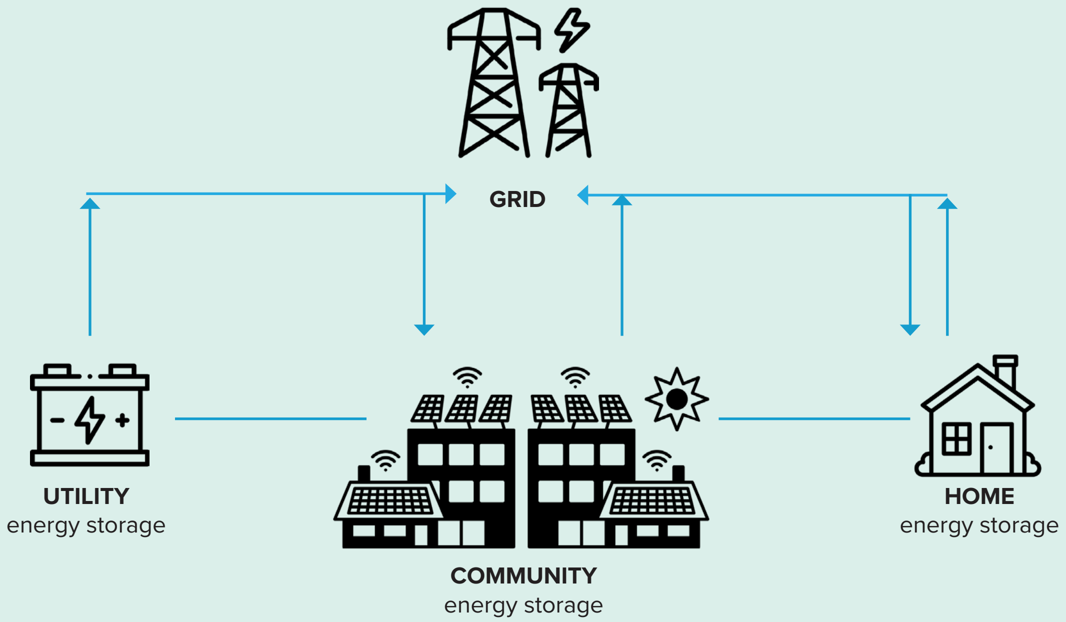
So logically, just like decentralised solar and wind generation assets, so will there be storage to match those. But that locational storage is not just simply short or long . It lies between these – in other words it's mid capacity and duration.

If we now reflect on the characteristics of short duration energy storage and those of long duration energy storage, and compare their technology characteristics to those best suited to the mid capacity and duration storage, then a picture will begin to unfold. And that picture is that there is currently a storage capacity and duration gap in the decentralised energy market we will refer to as mid duration storage.

In a nutshell: The schematic overleaf seeks to integrate the modularity, scale and duration of the mCAES/TES storage system with the modernisation of the small, medium, long storage capacity and duration in network development. The schematic shows a simplified grid bidirectional diagram at the top, followed by an again simplified potential mCAES collaboration with those three areas at the bottom.

It is not that much of a stretch to see how the energy storage facilities could interact digitally to provide an energy storage cloud.

SIMPLIFIED STORAGE SCHEMATIC



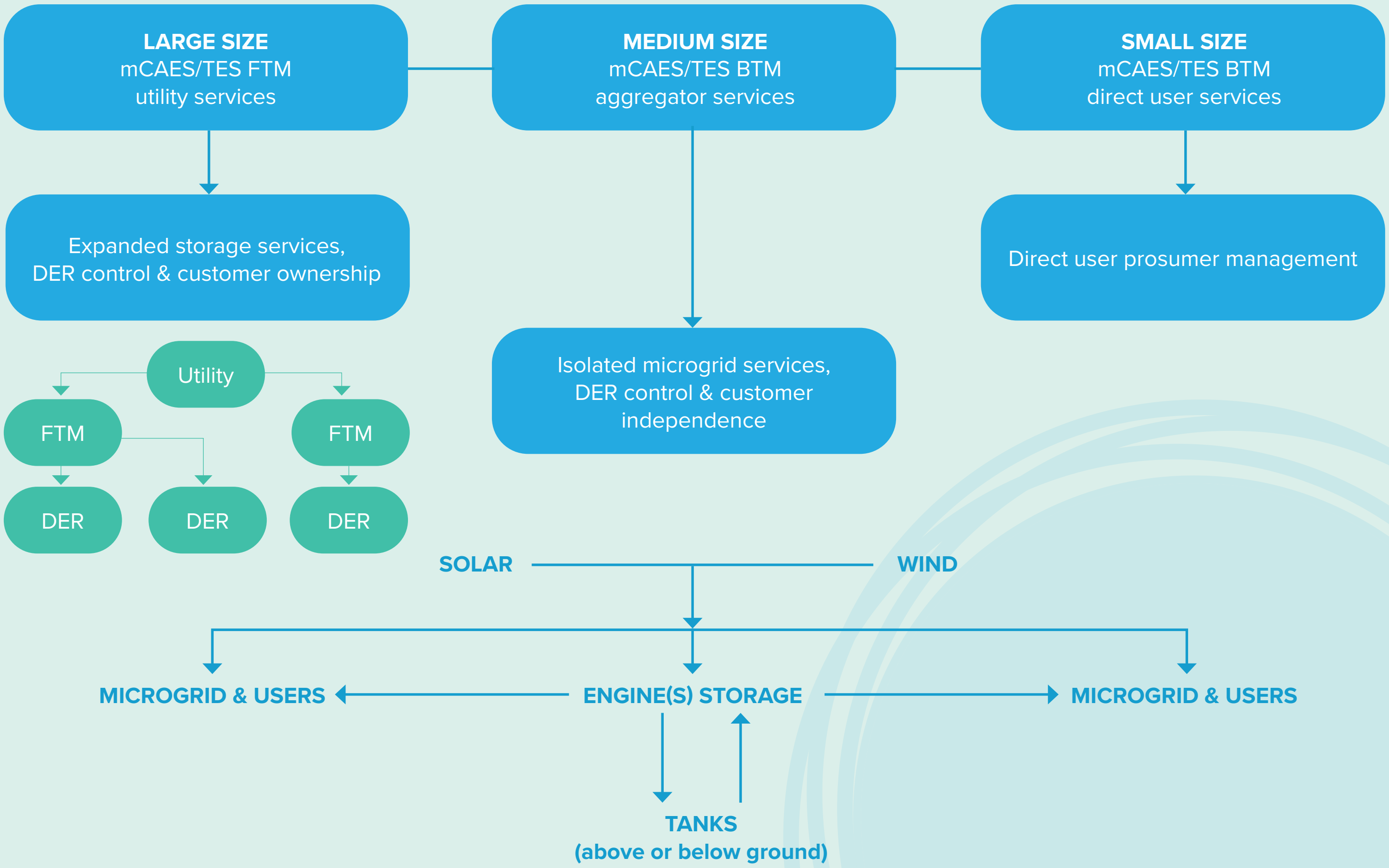
GRID

UTILITY
energy storage

COMMUNITY
energy storage

HOME
energy storage

POTENTIAL MCAES/TES COLLABORATION



LARGE SIZE
mCAES/TES FTM
utility services

MEDIUM SIZE
mCAES/TES BTM
aggregator services

SMALL SIZE
mCAES/TES BTM
direct user services

Expanded storage services,
DER control & customer ownership

Isolated microgrid services,
DER control & customer
independence

Direct user prosumer management

Utility

FTM

FTM

DER

DER

DER

SOLAR

WIND

MICROGRID & USERS

ENGINE(S) STORAGE

MICROGRID & USERS

TANKS
(above or below ground)

Refer to the Glossary for terms such as DER, FTM, BTM, and prosumer

3. mCAES/TES DECENTRALISED STORAGE

The R&D for the mCAES solution has been substantial, but to tackle the 51B tonnes GHG per year - that takes field solutions

Not much yet gets spoken about mid duration energy storage, but both short duration and long duration are known and very much in play. Most people are familiar with short duration battery storage, catering for a few hours of discharge, or long duration pumped hydro such as Snowy 2 in Australia. A recent cost estimate for that project was $12 billion plus any transmission additions - a large scale project, though way over its $2 billion original budget.

Long duration utility level storage has high capital cost, and are civil engineering type projects at fixed location. For sake of comparison here let us consider the large utility scale long duration compressed air energy storage (CAES).

CAES uses underground caverns or large storage pods to store air at high volume relatively low pressure, which is enabled via having a large space. Logically energy will be supplied wholesale or to very large direct customers. CAES is predominantly fixed storage and is not readily a mobile part of decentralised locational storage solutions.

mCAES primarily targets energy storage applications ranging from 1 kW to 10 MW, CAES focuses on a different scale, typically ranging from 10 MW to 100 MW, if not larger.

In contrast to CAES (or other fixed location long duration storage), mCAES mobile storage can be situated at or near the end-user, whether it's a building, a microgrid, or a solar or wind farm. The technology primarily focuses on the middle range of energy storage - above individual homes and below the massive scale of utility applications. Moreover, when thermal energy storage is integrated into the mCAES framework, it broadens the spectrum of services and applications the technology can support.

3.1 Mobility & modularity for decentralisation

The mCAES compressed air system design is fully developed and ready for deployment, as is the thermal energy optimisation by potentially adding external heat to air expansion. The front end adiabatic heat capture is being developed and is best completed in the field given the design flexibility scope.

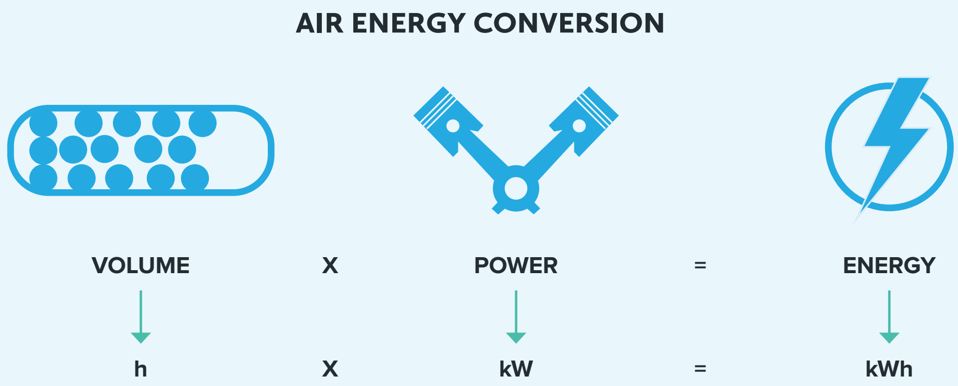
The system scope has been meticulously designed within the numerous MDI focus Labs, and has undergone real-world application in vehicle production commissioned by major clients. The energy focus has specifically been within the energy Air Lab using solar generation.

Manufacturing processes for mCAES are complete and for TES thermal optimisation is developed for cooling and optionally expanding the air on expansion via the low temperature burner option. This triples the range of the expansion. The last aspect of the thermal operation is the heat capture from compression to use within the system at the expansion stage or externally for heat applications for customers. This final stage is under development. These two aspects, mCAES and TES, operate asynchronously, but their manufacture is integrated. The unique nature of mCAES customer-needs requires a different approach to thermal optimisation compared to traditional CAES. mCAES adopts a strategy of trigeneration, providing customers with electricity, heating, and cooling solutions.

The mCAES storage system is comprised of fully modular components, anchored by a proprietary reversible air engine that is designed for maximum capacity, modularity, and efficiency. Its core functions encompass compression, driven by renewable energy sources such as solar and wind; storage, within steel or carbon fibre tanks (carbon for vehicle applications); and expansion, of stored energy through the air expansion applied to power an electricity generator or a vehicle.

Notably, the reversible engine carries out both compression and expansion functions, offering flexibility and efficiency. The tanks can be filled through a proprietary air filler, akin to an electric vehicle charger. The system is entirely modular, with the engine size, number of pistons, and tank configuration all being adjustable. The system's operation is controlled by software and artificial intelligence, ensuring smooth and efficient functionality. Torque remains constant, and power output can be adjusted through changes in engine revolutions. The pistons' operation can be controlled collectively or individually, thanks to the smart electropneumatic valve train.

For applications where weight is important carbon fibre tanks are used and composite materials for body work. Recyclable steel tanks are used in fixed locations.



Above: Unlike nearly all other storage systems, mCAES can separate (decouple) the power (kW) from the hours (air storage) making the energy supply (kWh) modular.

The mCAES technology

The following relates to components.

- **The Reversible Air Engine.** A patented and innovative component, functions both as an air compressor and an air expander, serving as the core of the energy storage and conversion system. The engine's modularity, variable sizing, and operational mode determine the system's capacity. Engines can also be assembled together, harmonizing with the generation source and storage tanks to match energy capacity and duration. The engine plays a pivotal role in thermal energy management, transitioning thermal energy from being a mere by-product to a conscious and beneficial service. For example, a 2-cylinder engine may have specifications of 430 cc, 20 kg, 7 kW at 1500 revolutions per minute, while a 3-cylinder engine may be 1000 cc, 50 kg. The choice between standardization and modularity enables adaptation to the diverse market conditions discussed in the next section.
- **Smart Piston Operation.** Modular piston management is a core aspect of the system. Beyond piston variability, pistons are managed through a smart electropneumatic valve train, resulting in smart cylinders. This approach allows for variations in the adiabatic and polytropic operation, optimising efficiency and enabling a wider range of applications. The smart electropneumatic valve train enables an extreme flexibility that makes a single engine applicable to various products. The rev-by-rev management of the engine, that ensure the adaptability of its performance, is a key point when connected to renewable energies. Despite these adjustments, the engine design is based on a conventional piston engine. The efficiency and power required to operate the converter as a compressor can be electronically modulated on a per-revolution basis.
- **Modular Storage Tanks.** Tanks offer the flexibility to be larger or smaller, added separately, operated in serial or parallel configurations, or any combination thereof. These tanks can also be placed underground for storage farms, with pressure adjusted based on the application. A small system may operate at a pressure of 248 bar. Carbon fibre tanks have an estimated lifespan of 20,000 cycles, equivalent to 20 - 30 years of usage. Their recycling process poses no chemical or physical issues. Carbon fibre tanks are subject to a filling test every 5 years and are appropriately certified, including the ability to withstand vehicle accidents without fragmentation. Steel tanks, employed for energy applications, use sustainable and non-toxic materials and are recyclable. Quick refilling can occur through an air station unit, such as for vehicles, or through renewable energy sources in energy applications. Importantly, there is no discharge or degradation; when the system is not in use, it remains 100% charged. The system is safe for use in inflammable environments, requires low maintenance, and is highly robust, capable of operating in various conditions, including remote locations. The software- controlled system is resistant to theft, making it suitable for remote and potentially vulnerable areas.
- **Variable Scale Applications.** One of the unique features of mCAES is its modularity, which allows for economical scalability across increasing capacity and duration. The ability to vary the system's scale also impacts its composition. For example, in a home setting with small capacity requirements, energy density is crucial as it affects space considerations. Higher tank pressure leads to more heat generation, with potential losses (referred to as "diabetic" systems), which could impact the system's front end efficiency. In contrast, in a microgrid storage farm application, energy density becomes less important, as tanks are not confined to limited spaces and may be situated underground.
- **Efficiency & Density.** The distinction between these applications is that in the first case (e.g., a home setting), a decrease in efficiency relative to a battery might necessitate the installation of additional solar panels to compensate for the energy loss. However, as the scale increases, such as in a microgrid scenario, both energy density and solar input become lower priorities compared to capacity scale and cost. In all cases, price remains a key factor, and mCAES has the potential to be considerably cheaper to manufacture and deliver. Comparatively an mCAES system may target a capacity range of 1 kW to 10 MW, while CAES systems typically cover the range from 10 MW to 100 MW. The design and specifications can be upgraded as needed to accommodate various commercial requirements, and these aspects will be further detailed in the next section.

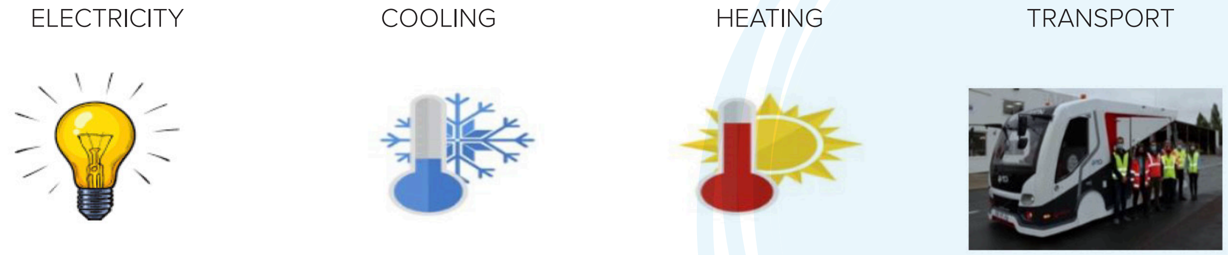
The TES technology

The thermal optimisation incorporating the compression stage thermal energy storage (TES) and the expansion stage air expansion via optional external heating are integral parts of the system.

> *“ Once fully applied this has the potential to become one of the most efficient and cost-effective generation energy and thermal storage solutions within the energy and storage modernisation framework ”*

- **Tripling duration.** Completed is the external low temperature burner as an optional part of the system to triple the range and duration. Also to date is the refrigeration and cooling potential generated at the expansion end of the system. The mCAES system features an optional low- temperature external burner, which can efficiently use biofuels. This heat is applied to the expansion process and triples the volume of air, thereby tripling the system’s range or duration while keeping the power output constant. This dual fuel option is particularly well-suited for remote locations. The energy derived from burning fuel is very efficient and cost-effective, as evidenced by its vehicle applications, which consume as little as 0.5 litres of fuel per 100 kilometres and generate virtually zero nitrogen oxide emissions and unburned hydrocarbons. Efficiencies at the expansion end are estimated to be around 70%.
- **Compression adiabatic heat capture.** The completed TES system, once it becomes an integral part of its thermal optimisation capabilities, will be able to provide efficient and sustainable heating, cooling, and HVAC (heating, ventilation & air conditioning). Completion of the front end (compression) of the TES system requires field collaboration due to the significant opportunities it presents, including scaled trigeneration from a single customer system. Heat generated during compression can be captured and subsequently applied during the expansion process, significantly increasing overall system efficiency.
- **Trigeneration.** For mCAES, this creates a substantial opportunity. Targeting mobile applications, mCAES exhibits higher energy density from a customer perspective due to its utilization of higher storage pressures, resulting in more heat generation during compression. When combined with the cold exhaust, this configuration transforms the mCAES system into a trigeneration system, capable of simultaneously providing electricity, heating, and cooling. With full modularity across integrated generation sources (e.g., local solar or wind) and the mCAES storage system, the focus is squarely on the customer’s needs.

One singular technology, four applications



SINGULAR TECHNOLOGY & SYSTEM → **FOUR APPLICATIONS**

A unique multi-application from a single energy generation & storage service. The future is bright and comfortable

3.2 Specifications ideal for storage & its manufacture

The mCAES specifications (recall storage characteristics listed earlier), especially when integrated with the TES system, have the potential for huge impact. However it is the modularity for energy storage scale specifically targeted to decentralised energy generation and users, that can impact a whole area of energy modernisation.

As we all know nowadays, demand is equally about supply. The mCAES/TES technology is ideally suited to taking that a step further to modular distributed micro manufacture. That can be undertaken either via outsourcing or turnkey production factories in regional locations across a country.

The following are some key points:

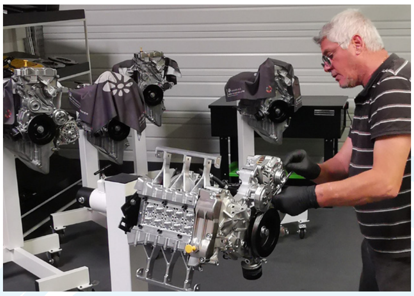
Production Outsourcing partners for market entry

- **Modular Component Manufacturing:** The production process for mCAES components is highly modular, both at the component level and the production level. This modularity allows for standardized components to be manufactured and assembled with ease. The engine is primarily based on a standard piston engine, while tanks and other components are standard.
- **Turnkey Manufacturing:** Manufacturing and assembly are turnkey processes, which means that all the necessary plans and designs are available for immediate implementation. This approach streamlines the manufacturing process, ensuring efficiency and consistency.
- **Scalability:** Manufacturing and assembly can be scaled progressively, from small-scale production to large volumes. This adaptability allows mCAES to meet market demands effectively and expand production as needed.
- **Outsourcing Partners:** The business philosophy of providing technology solutions rather than proprietary distribution channels extends to the initial manufacturing hub. Outsourcing partners are sought after for the advantages they bring, including expert management, regulatory compliance, and workplace safety. This approach makes it easier to assess the profitability of different market channels and lowers the capital requirements and risks.

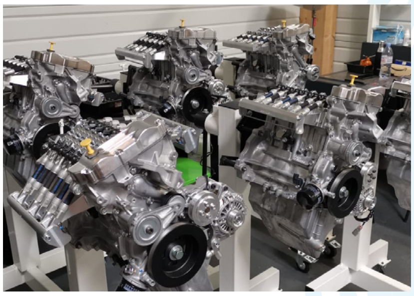
Manufacture is micro distributed. Enabling local wealth, employment, security & affordability.


Body panels


Carbon fibre tanks


Engine assembly


Electronic parts


Assembled engines


GreenAir for Expo

Modernising a centralised energy system
to incorporate a decentralised one

4. mCAES/TES DECENTRALISED MARKETS

For convenience we connect the capacity and scale with the duration, but that's not always the case. Mega batteries are large capacity but still short duration for their application. We categorise storage into three levels:

- **Small-scale storage:** For example home battery with relatively low energy demands, typically in the kilowatt (kW) capacity range and with a few hours of storage. This is characterised by fast response times, and short cycle times. Customers may include residential users, smaller businesses, and microgrids.
- **Mid-scale storage:** This falls between small scale and large scale, typically larger kW to smaller MW. We refer to it as "the rest" due to segment size. Customers include industrial, microgrids, virtual power plants.
- **Large-Scale storage.** At the large end is typically the utility fixed storage such as those referred to in this paper. These are characterised by slower response time, longer cycle time, and higher capacity in the smear to larger MW area..

> *"A primary theme of this paper is that affordable capacity, economic scale, and variable duration storage a key fundamental for energy and storage modernisation, and especially for decentralised energy"*

At the small end there is presently little competition with batteries due firstly to their market maturity, availability and promotion; secondly their high efficiency meaning less solar panels; thirdly their high energy density, and fourthly their users are not seeking long duration. Their overriding hurdle is price per capacity, which is causing a huge lag in battery versus solar panel sales.

At the middle end there is simply a gap. You have to use batteries or minimal equally expensive greenfield technology. And since batteries are short duration their price and other negatives soon become prohibitive, while their slam end positives lose their benefit. And batteries are not modular – so you buy what's on the rack.

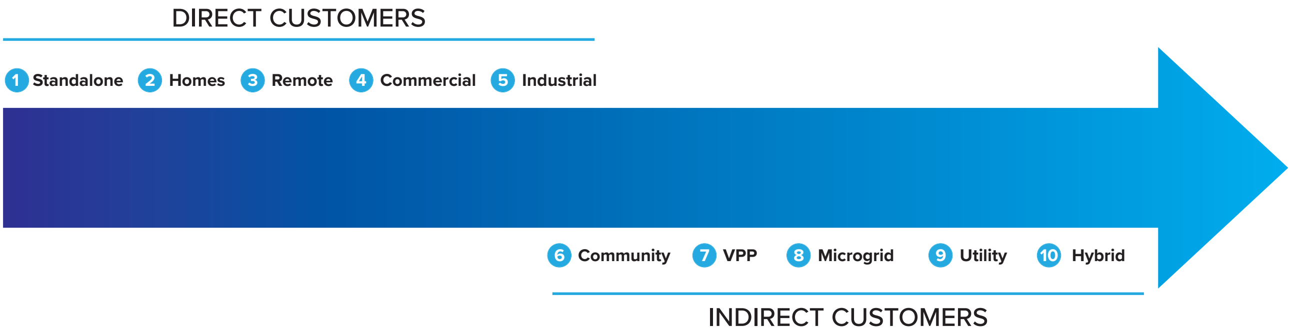
At the large end the only access generally from the middle end is via transmission and distribution, so it looks like grid, and doesn't provide local storage benefits.

The goal of these categorisations is not to be overly rigid with exact cut-off points, but to provide a conceptual framework for understanding the differentiation between storage users. One might expect some overlap at the margin, but as energy and storage modernisation moves towards tripling the energy, matching needs perfecting.

4.1 The middle duration decentralised storage gap

There is, at least to us, a logic in the preceding. Why would one look at storage as either small or large with no in between, as opposed to a continuum. Of course to provide for a continuum of storage capacity requires modular storage technology across capacity, economical scale, and duration.

The following schematic is a representation of the range of users from small to medium to large. Whilst the table provides insights into the diverse range of customers and the duration and capacity required for each segment, it does not show the huge scope of same within each segment.



THE mCAES/TES MARKETS POTENTIAL

Elaborating on the preceeding the next table adds some characteristics of those markets

Capacity kW INCREASING CAPACITY & CAPITAL Capacity MW

1 Standalone	2 Homes	3 Remote	4 Commercial	5 Industrial	6 Community	7 VPP	8 Microgrid	9 Utility	10 Hybrid
Isolated EVs	On or off grid	No grid	Businesses Buildings	Industries Centres	Home DER Farm DER	Public DERMS	Stand alone or integrated	Central trans'm CAES	Combine AEMO

SDES MDES LDES

INCREASING DURATION & CAPITAL

The first arrows show the increasing size of storage.
The second arrows show where the sizes fit for various markets.

Footnote: Farm refers to solar or storage farms. DER are distributed energy resources. DERMS are the management system for those. Trans'm is transmission. AEMO is the energy market operator. Capacity is a convenient size distinction, but kWh energy delivery is very relevant as we decouple the two providing great flexibility. Capacity and duration tend to be linked, although again we can decouple the two (for example tanks in parallel versus in serial changes the duration but not the capacity). And S, M, and L is small (say 4 hours), medium (say excess 10 hours) and large (days and above).

In the modernisation of the energy network there is a range of infrastructure, and the elements of generation, transmission, distribution and retail vary substantially. Across the electrified network the generation and usage benefit by having storage facilities.

Footnote: For any discussion on energy storage duration we consider capacity and duration together. It's not simply a home going off grid.

The preceding section is laying the groundwork for understanding how mCAES technology can cater to the specific needs of different market segments, especially focusing on middle-duration energy storage, and how it can contribute to the modernisation of the energy network by addressing storage needs in various sectors and applications. It sets the stage for exploring the contributions and applications of mCAES in more detail within these market segments.

Isolated, modular and affordable storage solutions are needed everywhere

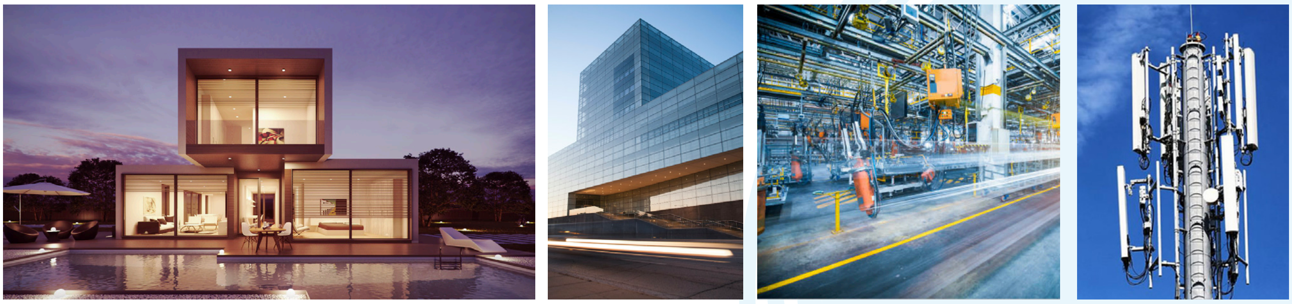
4.1 The middle duration decentralised storage gap continued

A practical scenario.

One new community based microgrid is looking to interconnect the distributed solar panels from 1,000 consumers and manage them across the owners and users (in this case users are the same), and feed in tariffs to the grid, via a digital intelligent management system. To be a participant you not only need panels, but you also need a battery. The sponsor will assist with the finance under an agreed commercial arrangement, and be provided a reward.

A second new community based microgrid still with 1,000 users is organising a local solar farm of equal capacity, and adjoining it a storage system. In the case of mCAES the storage tanks can be placed underground. To be a participant you need nothing up front, as was the preceding case, but also users can invest their own funds somewhat like a solar plot. In this case the digital management system separated out usage and provision of the energy assets. Now of course the solar and the storage becomes much higher scale.

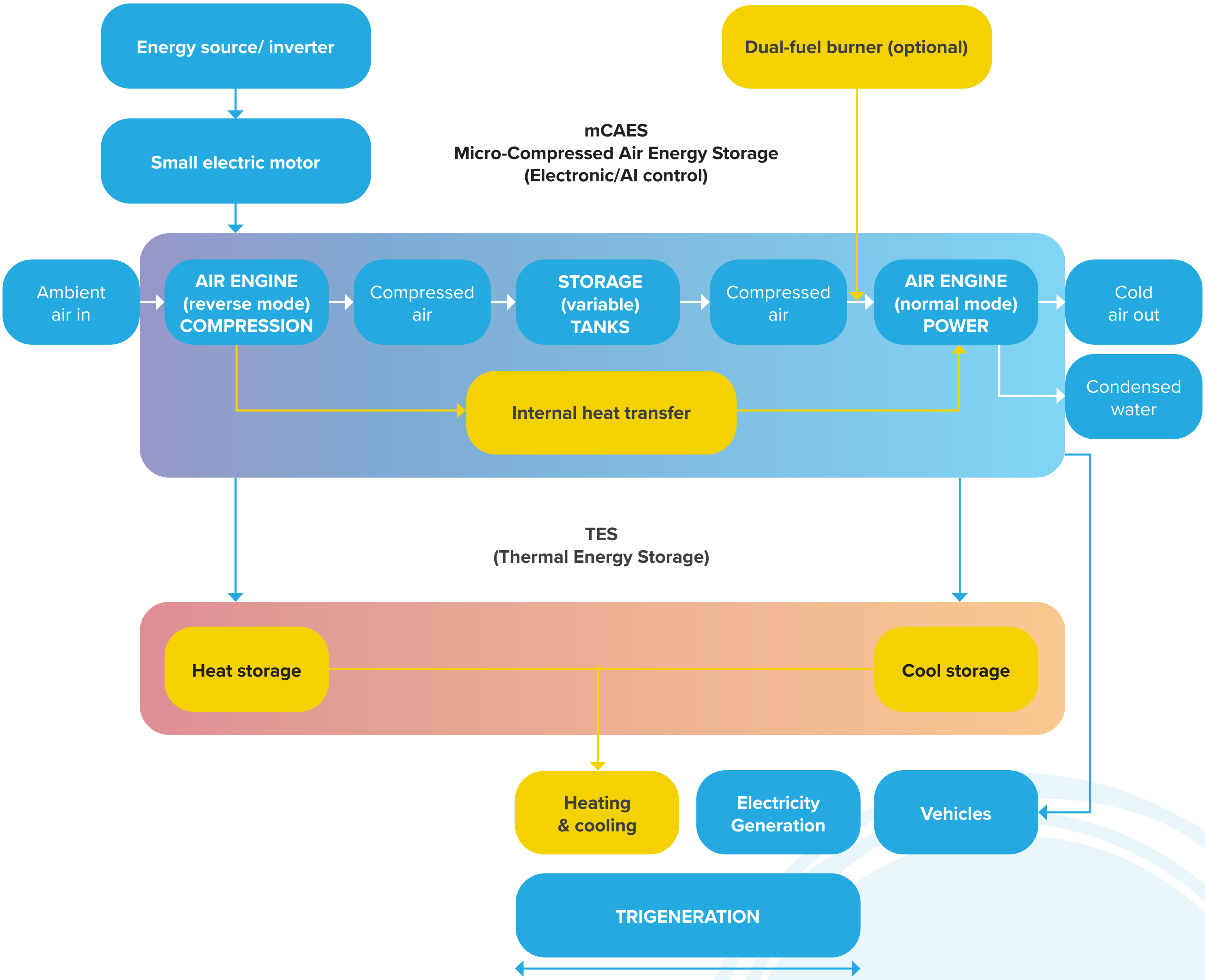
Clearly this is just a first step in the scaling of decentralised energy and storage with infinite possibilities.



Above: Applications can be at fixed or mobile locations

mCAES/TES system (core & advanced)

The integrated & modular energy storage & thermal optimisation system



Energy source/ inverter

Small electric motor

Dual-fuel burner (optional)

mCAES
Micro-Compressed Air Energy Storage
(Electronic/AI control)

Ambient air in

AIR ENGINE (reverse mode) COMPRESSION

Compressed air

STORAGE (variable) TANKS

Compressed air

AIR ENGINE (normal mode) POWER

Cold air out

Condensed water

Internal heat transfer

TES
(Thermal Energy Storage)

Heat storage

Cool storage

Heating & cooling

Electricity Generation

Vehicles

TRIGENERATION

4.2 Short & long duration – collaborating an energy storage cloud

In the preceding discussion focussing on matching storage to decentralised mid-size energy generation and usage (capacity, scale & duration), situations, it highlighted for that market there were small and large end constraints.

At the small end there is inadequate economical scale and duration. Batteries currently dominate the short-duration storage market but face constraints in terms of price, duration, and capacity scaling. They excel in terms of efficiency and energy density, daily cycling, and fast response.

At the large end there may be a price, duration and capacity constrain (as per mega utility batteries serving FCAS, backup, or time shift), or the constraint may be mobility and fixed location. Best understood via natural disasters or extreme weather.

It is the initial view that the mCAES/TES technology via its modularity, economical scaling, mobility, and duration could work in conjunction with the short and large end to add distributed benefits to outlying customers and networks. This is conceptual and the proposition is beyond this paper for future discussion with relevant parties.

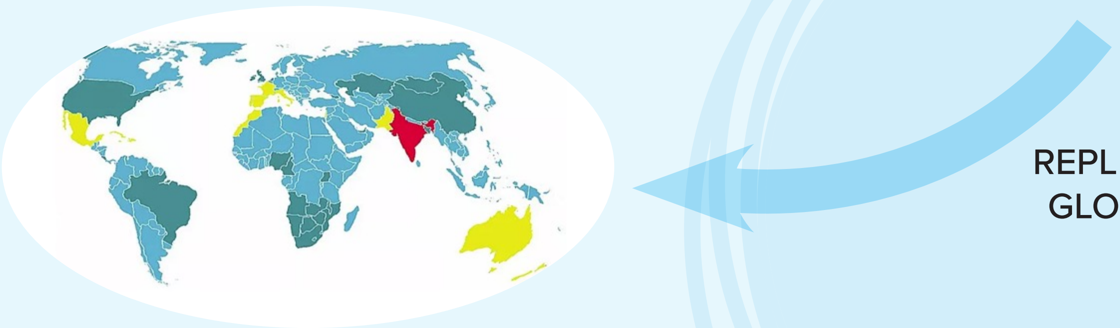
A fully modular system means an easy shift across storage requirement for capacity and duration. Capacity and energy delivery are decoupled (asynchronous) via engine and tanks independence

5. COMMERCIALSING AUSTRALASIA & GLOBAL REPLICATION

In our platform for Australasian commercialisation there are a number of distinct tasks being addressed:

A. The commercialisation platform
B. Completing the commercialisation platform
C. Securing the technology & manufacturing IP
D. Progressing manufacturing outsourcing partner
E. Distribution relationships with market channels
F. Development relationships with technical partners
G. Investors, funders, and government relationships
H. Preliminary replication relationships with regions

The first item **A.** addresses the all-important human resources and corporate structure.

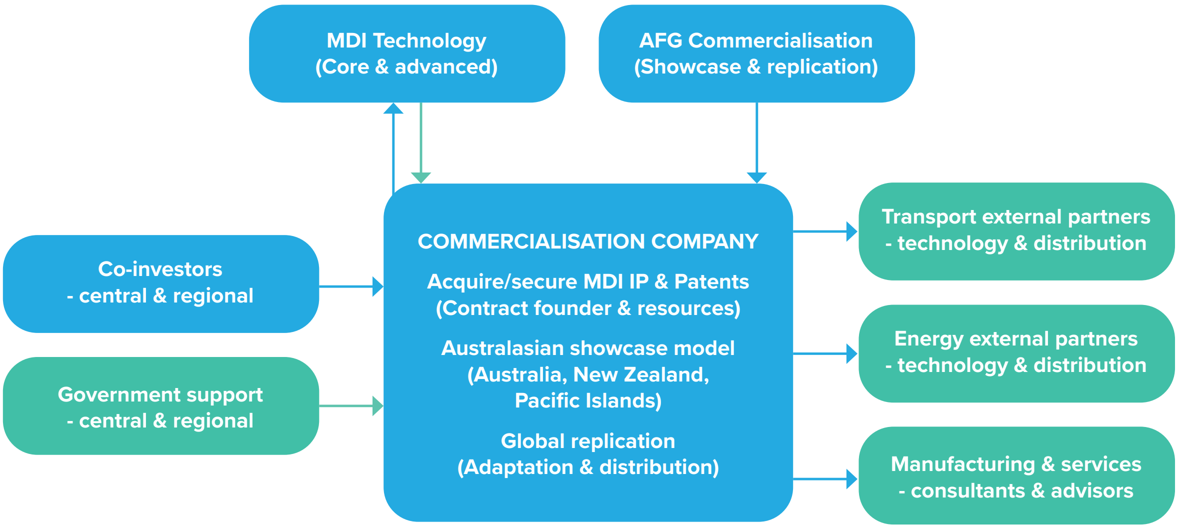


REPLICABLE GLOBALLY

5.1 Human resources – team & partners

AFG and MDI are small companies and historically have been flexible in resources, catering to the tasks at hand. The next stage of mass commercialisation progressively requires a more permanent base, except for project work.

However the commercialisation company, which we refer to as AF-MDI, will function predominantly via channels and partners due to the diverse range of our markets.



MDI Technology
(Core & advanced)

AFG Commercialisation
(Showcase & replication)

Co-investors
- central & regional

Government support
- central & regional

COMMERCIALISATION COMPANY

Acquire/secure MDI IP & Patents
(Contract founder & resources)

Australasian showcase model
(Australia, New Zealand,
Pacific Islands)

Global replication
(Adaptation & distribution)

Transport external partners
- technology & distribution

Energy external partners
- technology & distribution

Manufacturing & services
- consultants & advisors

Collaborating and enabling storage modernisation solutions via market partners

Executive team

The platform's initial executive team consist of the AFG Chairman and CEO and the MDI President. The following are some company and executive details.

RUSSELL FITTS
Chairman

Russell has been executive chairman of all companies since incorporation. He has led the incubating company through its various progressions to position it with the operating group and exclusive licence rights for all of Australasia. His personal relationship with the licensor and his global network of contacts has laid the foundation for growth via commercialisation. His prior experience in farming and business earned respect by contributing as a Senior Member of the NZ Property Institute and servicing the NZ Earthquake Commission.

JOHN MENNEGA
Group CEO

John has an MBA, BE(Elect Eng), Grad Dip (Industrial Eng), and Grad Dip (Applied Finance & Investment). His background spans engineering, finance, investment banking, and management with significant experience in early-stage business roll-out & growth. He has held top level executive roles in major Australian listed companies before devoting his experience to advising both middle and smaller companies on achieving financial & operating goals.

DR CYRIL NÈGRE
MDI President

Cyril is the President of MDI and Director of MDI R & D. He holds a PhD in Mechanical Engineering, and began his career in Bugatti Automobile car design, joining his family's company MDI in 1993. Cyril is AFG's key contact within MDI and organises and coordinates the support of their team. AFG's Director level strong personal relationship and investment with MDI goes back to Cyril's deceased father and founder Guy, and then closely with Cyril.

Team to be built across markets via recruitment and partners

Introducing MDI

MDI Sa is based in Luxembourg and was founded by the current President Cyril Negre's father Guy Negre back when the company was called Motor Development International. Both Guy and Cyril were acknowledged experts in their field prior to MDI. Cyril has been supported by an expert team of MDI engineers, plus technical collaboration with a number of the world's largest corporations. Cyril's father established the business focused on transport, with a belief grounded in compressed air powering a new-era designed car. The vehicle side was clearly established via MDI being commissioned for air powered waste vehicles and commuter transport for the Dubai World Expo (see photos in Addendum).

Cyril took the company into energy, recognising the modernisation of energy with climate change and the gaps in energy storage. Energy remains his immediate priority, as the transport side is technologically mature (but not mass commercialisation). The following can be said about MDI.

- Cyril and his engineers are passionate about the technology and wish to see it completed in the field and mass commercialised. Their role in transferring the technology from the laboratory and major bespoke customers to mass commercial field applications would complete a very successful R&D era.
- The technical team and Cyril recognise that technical is where their expertise and contribution best lie, and in the technology's continued advancement and in support of its mass commercialisation.
- MDI were impacted financially by Covid. The ultimate financial blow was that their then current commissioning client, the World Expo, deferred from 2020 to 2021, and the MDI family company had to carry the expenditure and changes resulting.

Together these factors have opened the door for a complete MDI restructure and focus on mass commercialisation as outlined in this paper.

Introducing Air Future

Air Future Group Pty Ltd (AFG) is based in Australia and is the commercialising partner of MDI. AFG has been backed by its incubating company Air Future Limited (AFL) based in New Zealand. AFL ceased their wireless telecommunication innovation business, following the advent of fibre cable, to focus on energy and climate change. AFL has been MDI's closest partner for over a decade, and after numerous working sessions in France decided to dedicate their climate passion to commercialising the MDI technology across Australasia, with global replication.

So was formed an enduring partnership. MDI technical development took longer than expected, reflecting the technology's intricacies and the small family company resources level (around 25 personnel plus consultants during development and transport clients). AFL assisted where appropriate in incubation for MDI.

The following can be said about AFG:

- An intense commitment to create a regional showcase of the technology's potential, and then replicate that globally.
- The intention to build the platform and create the opportunity for the longstanding contributors and new ones to benefit from their ongoing commitment.
- The desire to innovatively integrate both central AFG platform funding with regional distributed growth funding to fast track the potential of the technology and the business.

5.2 Financial resources – investors & funders

AFG is concurrently focused on working capital investment to secure the commercialisation platform, and cornerstone funders to back the rollout of the business. This paper acts as an introduction to the business, the technology, and the markets and operations (via distribution). Whilst the technology is commercialisation ready, mass commercialisation is at commencement (only commissioned transport projects have been completed to date).

No attempt has been made to include financial and commercial numbers in this paper. With working capital funding that will be an initial task.

1. AFG-MDI restructure
2. Securing the technology
3. Establishing the commercialisation resources
4. Projects establishing market distribution & support

The above is focussed on the commercialisation platform. Regional replication can be funded regionally.

Multiple refill options including the simple and speedy refill station

United Nations

POWERING THE FUTURE WE WANT
UN-DESA ENERGY GRANT 2016

POWERING THE FUTURE WE WANT

Recognizing leadership and innovative practices in energy for sustainable development - supported by China Energy Fund Committee

This certificate is awarded to

Motor Development International SA

in recognition of the contribution to advancing Energy for Sustainable Transport

WU Hongbo
Under-Secretary-General
for Economic and Social Affairs

New York
14 December 2016

Above: A climate driven evolution is not only an opportunty for the remote - it's an essential.

Right: United Nations award to MDI entitled "Powering The Future We Want".

ACTION PLAN

AF-MDI seeks potential investors, funders, and partners, to express interest to learn more and potentially participate in rollout plans for the mCAES/TES technology. These rollout plans can be in parallel and at various levels (such as corporate, projects, manufacture, recruitment, regional). AF-MDI will work together with parties to execute agreed action plan and its milestones in accordance with agreed resources and support.

AF-MDI does not seek to progress the business in isolation of the parties to the right, and will prioritise in accordingly.

Investment & Funding

Investors for general working capital and funders for specific projects, markets, or regions.

Market Partners

Parties for collaboration to progress market distribution and services. This includes the three levels of storage.

Technology Partners

Parties interested in implementing and developing the technology for field applications. This includes manufacturing.

ADDENDUM

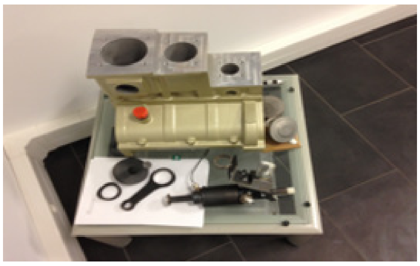
The air engine lab

The composite materials lab

The storage lab

The premises solar lab

Biofuel external burner



The markets team

Specialised laboratories were deployed across all the mCAES innovations

Above and below are examples of commissioned mCAES vehicle

Modularity demonstrated across many vehicle models

Transport, the first focus, enabled demonstrating vehicle modularity

GLOSSARY & ACRONYMS

The following is not intended as a generic definition, but rather in relation to the content of this paper.

1. LCOE (Levelised Cost of Electricity): LCOE is a measure of the total cost of generating electricity over the lifetime of a system, often expressed per megawatt-hour. It allows for comparisons of traditional fossil fuel and renewable energy generation sources. The latter is now viewed to provide cheaper sources for new generation. LCOE may not account for the full range of costs, such as grid integration or environmental impacts, providing an incomplete cost picture. Hence such single digit comparisons are overly simplistic for major decisions.

2. LCOS (Levelised Cost of Storage): LCOS isolates the cost of energy storage, similarly providing a single number comparison such as $/kW or $/kWh. However, storage systems are extremely variable, and future predictions very subject to assumptions, those assumptions including capital costs and conversion costs, let alone accounting for applications or multiple services provided. LCOS for mCAES/TES is a particularly inaccurate comparison in comparing to utility storage systems due to negligible capital cost and modularity enabling multiple application scenarios.

3. Microgrid: A microgrid is a localised energy system that can operate independently or in conjunction with the main grid, offering increased reliability and resilience for a specific area. Microgrids facilitate decentralised generation and storage and are considered as a platform for energy decentralisation. Microgrids are what we describe as middle capacity and duration in between homes and utility. They are a major opportunity for mCAES/TES contribution potential for climate emissions, affordability, and increasing duration.

4. BTM (Behind-the-Meter): BTM refers to energy generation or storage systems installed on the customer's side of the utility meter, often for self-consumption or demand management. BTM systems may not provide grid-wide benefits or support grid stability, potentially limiting their broader utility. On the other hand there is also the opportunity for utilities to develop FTM (Front-of-the-Meter) similar systems for a broader base.

5. VPP (Virtual Power Plant): VPP is a network of distributed energy resources (generation, storage, digital management) that can be remotely controlled and coordinated to provide grid services, enhancing grid stability and reliability, and broader customer service. Coordination of VPP can become a major consideration.

6. DERMS (Distributed Energy Resource Management System): DERMS is a software platform that optimises the performance and integration of distributed energy resources, such as solar panels and energy storage. DERMS are smart systems enabled as part of the digital evolution. Their role is especially relevant in future coordinated decentralised energy networks.

7. Solar farm: A solar farm is a medium to large-scale facility that generates electricity from solar panels, typically covering a broader land area and with numerous photovoltaic modules. Solar farms can not only provide economies and space for decentralised generation, they can complement mCAES/TES in provision of localised medium storage services. Together these will be a catalyst for microgrid and VPP economics, duration and capacity.

8. Digital: Digital refers to the use of advanced technologies like sensors, data analytics, and control systems to optimise energy storage and grid management. Digital systems related to DER management continue to develop at a fast pace. Like all digital internet or cloud systems cybersecurity is an integral element.

9. Legacy: Legacy systems or technologies are older, often outdated, and will eventually need to be replaced or upgraded to incorporate modern energy solutions. This creates a challenge in transitioning from a reliance on legacy systems to economically and commercially provide electricity whilst simultaneously phasing them out.

10. CCS (Carbon Capture and Storage): CCS is a technology that captures carbon dioxide emissions from industrial processes or power plants and stores them underground. Presently CCS is very expensive and still a developing technology. Obviously there is a fear in storing carbon underground with mankind's experience in oil spills, oil fires, and nuclear disasters.

GLOSSARY & ACRONYMS CONTINUED

11. Utility: A utility is a company or organisation responsible for providing essential services, in this case electricity. There may be some views that traditional utilities can be slow to adapt to new technologies and may face resistance in transitioning to cleaner energy sources.

12. Transmission: Transmission refers to the high-voltage power lines and infrastructure that transport electricity from power plants to local distribution networks. Building new transmission infrastructure can be time-consuming and face regulatory and environmental hurdles, plus can be very expansive and carbon generating.

13. CAES (Compressed Air Energy Storage): CAES is a technology that stores energy by compressing air and later releasing it to generate electricity. CAES is experiencing a strong surge in interest and investment due to the need for long duration and high-capacity storage as the world progresses to renewable energy.

14. Embedded: Embedded carbons refers to the extent of carbon emissions created in bringing a product or service into effect. So for an electric vehicles this may include mining, manufacture, distribution, warehousing and so forth. His is a carbon debt that needs to be amortised to have proved a green benefit. Solar is another example – the more the solar can be used the more the embedded carbons are amortised (like amortising the capital or finance to buy). Hence we have grey, blue or green hydrogen reflecting the carbon debt from production. mCAES/TES can provide a significant benefit in enabling faster amortisation (greater solar usage).

15. Trigeneration: Trigeneration is a combined energy generation system that simultaneously produces electricity, heating, and cooling from a single energy source. An mCAES/TES is a trigeneration system.

16. FCAS (Frequency Control Ancillary Services): FCAS are grid services provided by energy storage systems to maintain grid frequency within acceptable limits, ensuring stable power supply. FCAS is a key service for fast response high cycle batteries.

17. BESS (Battery Energy Storage System): BESS is a system that stores electricity in batteries for later use, potentially contributing to grid stability, load management, and renewable energy integration. The alternative systems are non-BESS such as pumped hydro or CAES.

18. Intermittent: Intermittent energy sources, like wind and solar, produce power irregularly, which can be smoothed out using energy storage solutions for consistent energy supply. Intermittent energy sources require complementary storage solutions to provide continuous power, adding complexity and cost.

19. Storage: Energy storage involves capturing and storing energy for later use, improving grid reliability and enabling the integration of renewable energy sources. Energy storage technologies may be judged by component efficiency (such as RTE round trip efficiency) or energy density being the space efficiency. However these terms have been built around familiarity with batteries that are basically components rather than flexible and modular systems tailored to applications. Here the term efficacy might be more suitable.

20. Transition: The energy transition refers to the shift from fossil fuels to cleaner, more sustainable energy sources and technologies, including the adoption of energy storage systems to support this change. The energy transition involves challenges in phasing out existing infrastructure, causing economic and employment disruptions in certain regions.

21. DER: Distributed energy resources. For example solar panels, battery, metering.

22. Prosumer: Simultaneously an electricity producer and consumer. For example home solar.