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Evaluation of "Battery-as-a-Service" Business Models for Rechargeable Batteries

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Executive Summary

While the notion "Battery-as-a-Service" has been used in the energy and automotive sectors for many years, there are numerous different business models for rechargeable batteries subsumed under the name. In this paper, we categorize and systematize different service models, as well as evaluate their technical viability and economic potential. In the closing chapter, we provide an outlook towards an optimal business model.

As a conclusion, we find that "Battery-as-a-Service" business models have common characteristics across different applications but require different technical implementations. Realizing the physical separation of rechargeable batteries for mobile devices including "battery swapping" poses technical and operational challenges, while adapting battery capacity to individual use cases provides sustainable financial advantages.

Keywords: #electric vehicles, #batteries, #light electric vehicles & Micro Mobility, #Design for second life, #Energy storage systems

1 Introduction

The first documented uses of the notion "Battery-as-a-Service" can be traced back to rental companies, providing lead-acid batteries as temporary UPS (Uninterruptible Power Supply) to critical infrastructure such as hospitals, data/ computer centers, financial institutions or telecommunication hubs during repair and construction periods, but also for risk mitigation of natural disasters or armed conflict. A highly distributed and competitive network of both localized as well as national and international rental or leasing companies for such assets exists.[1]

During the emergence of electric bicycles and scooters (and other Light Electric Vehicles (LEV)), the term was increasingly used to advertise the provision of professional services for the charging, maintenance and repair of their batteries, especially in rental businesses or urban bike sharing. In selected cases such as the Taiwanese mobility provider GOGORO, users were prompted to swap the batteries of rented electric scooters at central service locations.[2]

Recently, the term "Battery-as-a-Service" has been used to denote a battery swapping system by NIO, a Chinese start-up manufacturer of electric passenger cars.[3] In different global regions, different business models are applied, combining a variety of separate ownership models for vehicles and batteries of the manufacturer. While all batteries – even across different vehicle models and brands of the same manufacturer – adhere to the same physical dimensions, there are different charging capacities available.

These three actual examples serve to illustrate that the notion "Battery-as-a-Service" is used in a variety of industries and for a wide variety of purposes. It is the intention of this enquiry to analyze these different models for their underlying business logic from a supplier perspective and identify the technical prerequisites enabling each of the business models as well as the commonalities between the models. Without referring to real values, the key factors for the financial validity for each business model will be identified in order to derive a set of key characteristics for a common definition and an ideal "Battery-as-a-Service" business model. Given the accelerating transformation of the generation and provision of energy from consumptive and continuous to regenerative and cyclical sources, the relevance of energy storage increases accordingly.

2 UPS Rental Services

Uninterruptible Power Supplies (UPS) can be classified into off-line or standby UPS, line-interactive UPS and on-line UPS. [4] The revenue model is based on a per-period rental fee for the provided hardware comprising mostly battery storage, but also rectifiers/ transformers and corresponding cables and connectors as well as surveillance and operations. Rental providers typically include both the cost for conveying as well as setting up the installation in the rental fee. [5] During a period of employment, the provided battery storage capacity remains unchanged, while the required capacity and power can be assessed and specified before deployment – adding an element of customization. Only in the case of off-line UPS, the stored energy content is part of the fee, while in all other cases, available electric power is used for charging aka re-charging the battery storage based on the user's existing energy infrastructure and contracts. Grid integration or smart, bidirectional charging services are not applied in favor of the main, critical energy load.

2.1 Business Model

Uninterruptible Power Supplies are a special case of Power Generators, which have a long history of providing electrical power and/or heat to technical installations with lacking internal energy resources. While Power Generators serve the purpose of permanently supplying energy, Uninterruptible Power Supplies serve the purpose of securing temporary energy provision when the permanent supply gets interrupted. In the case of electric power, permanent supply is provided by connections to the general power grid which is served by numerous energy sources at different locations, therefore guaranteeing a high level of confidence. However, some industrial or domestic processes are sensitive to even the slightest interruption of electrical supply and create significant direct and indirect cost after an unscheduled or unintended break. Direct cost may be in the damage of half-finished goods in a production process, the loss of data in a software program, or the loss of revenue for the energy provider. Indirect cost may be much higher, when for example a machine gets damaged in an interruption (e.g. from the stalling of molten metal or glass), lost data need to be recovered or re-created, or damages need to be paid for breaching contractual delivery terms.

The business model of UPS providers is based on the avoidance of direct and indirect interruption cost. This value proposition allows value-based pricing strategies based on the amount of possible damages incurred from a single – or multiple - interruption, independent of the actual cost of the UPS – but also independent of the probability of the event. However, since UPS provision is a wide-spread and established business, actual pricing underlies significant competitive pressures and can be expected at or near actual cost comprising the battery system, but also transport, installation, service, observation, deinstallation and removal after use. While some applications would require UPS support over their entire operational life, others may only be temporarily exposed to the risk of interruptions of power supplies. In the former case, the operator of the original application would be prompted to buy or lease the UPS together with the underlying technology as a permanent addition – examples are to be found in telecommunications equipment, hospitals, computer centers, or execution of highly temperature-sensitive production processes such as pressing glass, aluminum injection molding, or deep-freeze pharmaceutical compounding. Although the UPS could be based on battery technology, in this case the notion of "Battery-as-a-Service" would not apply. However, if the period of expected interruptions is more limited and foreseeable, operators would usually opt to only temporarily rent or lease the potentially required amount of power and/or energy, constituting a true "Battery-as-a-Service "use case.

2.2 Technical Prerequisites

From a technical point of view, the main requirement for a UPS is its interoperability with the application it is intended to support, usually achieved by adaptability and compatibility of the technical configuration. Therefore, the process of specification of technical requirements for the UPS as well as intended modes of power transfer constitutes a core element of a "Battery-as-a-Service" deployment. Based on requirements, the UPS battery system will be configured to provide an optimal match to the intended application – starting with the determination of alternating vs. continuous (AC vs. DC) current provision, number of active phases, electrical earthing, galvanic separation, required voltage and insulation as well as communication interfaces and protocols. Only then, expected power demand, duration and frequency of disruption, available energy sources and other performance-oriented factors are considered for determining the most efficient battery system configuration.

Therefore, UPS battery systems in a Battery-as-a-Service use case need to be highly scalable and adaptable to their intended use and context of deployment. While some providers – with very large and varied fleets of integrated battery systems – may choose to propose their customers with the “closest match” from their existing choice of systems, they run the risk of overfulfilling the actual requirements and therefore offering an oversized system at a too-low price (alternatively, they may face significant fines if they provide an undersized system which fails to deliver to specification in the given case). For fully-flexible and efficient system configuration, modular and scalable battery systems are used – for example, through a combination of several smaller one-phase systems to provide multi-phase output, or the re-patching of separate battery systems installed within a larger containment, such as a 20-ft or 40-ft sea container.

2.3 Evaluation

Battery-based Uninterruptible Power Supplies show many technical characteristics that are common to many Battery-as-a-Service models – it may even be considered the “blueprint” for such business models with a long heritage and multi-faceted experience in providing on-demand energy in both on-grid as well as off-grid environments. However, since they are normally not intended for actual or regular use – one may almost say that they are intended to never be needed – their energy delivery is minimal and would not form a reasonable base for pricing or remuneration. Therefore, current pricing models for battery-based UPS are an example of a flexibility- or capacity-based market and mostly consider the duration of deployment as the main driver based on the expected total life span and ongoing depreciation of the system. In addition, since the industry is highly competitive – and battery-based UPS are still under pressure from highly established combustion-engine based UPS technologies – pricing would not allow for high markups over actual cost and therefore, profitability. Business models can be significantly improved in on-grid use cases, when the battery is not only used in case of a grid breakdown, but actively provides smart charging services and receives additional remuneration for providing flexibility and capacity to the local power management system of the general electricity grid.

3 LEV Battery Swapping Services

The concept of battery swapping in Light Electric Vehicles – namely, 2-wheel scooters – was first introduced by Gogoro, a Taiwanese charging infrastructure company, starting in 2011. Gogoro announced a battery-swapping network under the name Gogoro Energy Network, designed to be deployed in cities for electric recharging of two-wheel vehicles like scooters, mopeds, and motorcycles. Riders swap out depleted batteries at a network of kiosks called GoStations for a monthly subscription fee. Scooters are equipped to handle either one or two standardized battery packs, allowing users to adjust the amount and rental fees for the full batteries to their requirements. However, grid-based charging of the scooters is not possible. Several competing consortia and initiatives attempting to standardize LEV batteries exist worldwide.

3.1 Business Model

Gogoro was founded in 2011 as a software company that supports LEV battery swapping. The Gogoro Network provides a battery swapping platform for LEVs in several countries in Asia. A monthly subscription provides users with easy access to fully charged, ready-to-swap smart batteries on the go, while users originally had to buy the scooter for their own use, thus separating the scooter and the batteries in ownership and financial model. Gogoro offers different subscription plans depending on usage, e.g. a flex plan for single battery use, or high usage (dual battery use). In 2019, Gogoro piloted GoShare, an LEV rental platform in Taoyuan city, Taiwan, in collaboration with the local government. The initiative has now expanded to other cities in Taiwan. As for GoShare, the pricing depends on rental duration and vehicle type. Gogoro works closely with local governments and businesses to set up a network of GoStations that can feed into the national grid. Gogoro use AI and a big data-backed platform to optimize battery swapping efficiency. [2]

Soon after launching in Taiwan, Gogoro collaborated with the German Bosch group (a major producer of automotive components and systems, but also of electric household appliances and power tools) to expand the business model globally under the brand “Coup”. Other than in Taiwan where the first business model entailed a combination of purchasing the scooters and subscribing to the swappable batteries, the European model implemented for example in Berlin (2016), Paris (2017); Madrid (2018) and other cities were a fully-integrated rental model following the “shared mobility” vision of transforming urban traffic. Other than in Taiwan, where owners were swapping the batteries themselves at the numerous GoStations distributed widely over the operating area of the service, the European models relied on a two-stage swapping system. While users were primed to exchange batteries themselves at one of very few swapping stations with rental time bonuses, the majority of re-charging operations were performed by company employees with batteries from one central charging hub. All operations were ended due to lacking profitability by 2019, and the remaining assets were sold in 2020. [6]

Other shared-mobility services have started to adopt the battery-swapping approach for their Light Electric Vehicles, such as electric kick-scooters or e-bikes. While still lacking the efficiency of user-enables swapping, the exchange of depleted batteries with fully-charged ones by company operators (aka “jockeys”) is logistically more efficient than collecting entire vehicles from all over the operational area, transporting them to a central charging location and distributing them to their pickup-locations after charging the integrated batteries.

3.2 Technical Prerequisites

The first electric Gogoro scooter was originally presented at the CES fair in Las Vegas in January 2015, with the battery-swapping capability as outstanding feature – along with a generally high-quality appeal and high-tech features as such as integrated LCD display and LED headlights. Even in the first generation, the scooter offered the option to operate with either one or two battery modules, in addition to an excessively slow and unattractive wire-bound charging option. As an accessory, a two-battery at-home charging pod called GoCharger is offered by Gogoro, short-wiring the financially efficient BaaS-model to a merely convenience-driven local swapping system, requiring the purchase of additional equipment. The battery modules weigh about 9 kilograms each and offer about 1.4 kWh (1st generation) or 1.7 kWh (3rd generation) usable energy capacity. The electric connector is described as “orientation-agnostic” and proprietary to Gogoro and compatible light electric vehicles (compatible brands include: A-Motor, emoving, eReady, PGO, YADEA, Yamaha, Awayspeed, and others). [7] The electric voltage of a battery pack is nominal 48 Volt; two packs in a vehicle will be operated in parallel to only increase capacity, but not power. In addition to the electric connection, the battery connector provides 8 additional pins for safety and communication interface. The battery packs also provide NFC-based connectivity with the vehicle as well as the user’s smartphone. A recent Chinese-US copy-cat of the Gogoro battery system works on a 12 Volt basis [8], adding further complexity to a market already lacking interoperability. In 2021, a number of Light Electric Vehicle manufacturers teamed up in the European-centric Swappable Batteries Motorcycle Consortium (SBMC), founded by Honda Motors, KTM, Piaggio and Yamaha [9] – but not Gogoro or their corporate partners.

3.3 Evaluation

While Light Electric Vehicles have a natural fit to Battery-as-a-Service business models due to the continuous financial pressure on users and limited discretionary spending power of buyers, commercially successful models are rare while a number of failed attempts seem to prove lacking viability. Evaluating the Gogoro example, it seems that the strict economic separation of batteries and electric devices is not only an optional, but a required element of BaaS implementations – even as extremely diverse as purchasing the vehicle and subscribing to the batteries. It seems that user expectations and habits are quite different between vehicles and their auxiliary features such as insurance, servicing and charging. However, discussions of these models have mostly focused on technical aspects of battery swapping instead of the business and service side. A salient example of such a technology – and thereby, problems-driven – approach is the very set-up of the SBMC consortium, which is fully focused on enabling technical interoperability by forcing a general technical norm on all possible applications, instead of taking a solutions-oriented approach concentrating on viable use cases and deriving the most efficient technical substrate from it. However, the technology-driven top-down approaches are constantly being undermined by grassroots projects in uncommon locations, such as the Swedish-supported motorcycle manufacturer Roam from Nairobi, Kenia, or Honda India's own Mobile Power Pack in a so-called "e-MaaS" (electric Mobility-as-a-Service) business model. While it seems that Battery-as-a Service in Light Electric Vehicles is still in its infancy, the number of independent initiatives suggest a significant economic potential while cross-system interoperability is not yet a major consideration.

4 Vehicle Battery Swapping Services

Based on development work at its predecessor company NEXT EV, the Chinese automaker startup NIO is currently the only passenger-car company to market a "Battery-as-a-Service" system. In this case, it comprises a uniform vehicle architecture allowing for the use of a standardized battery pack across all vehicle lines of the manufacturer. Another important element of the system is a network of self-owned battery-swapping stations in core sales markets, which are increasingly equipped to operate in grid-serving "smart" ways – and receive corresponding fees from grid operators. Although standardized in geometry and interface, battery packs are available in different charging capacity sizes, with purchase price and/ or rental fee varying accordingly. In addition, the vehicles offer conventional, cable-bound charging. Other segments deploying similar systems are documented for taxis in the city of Shenzhen [11], as well as heavy trucks in on-road and off-highway use in China. Experimental applications for commercial vehicles have also started in Europe.

4.1 Business Model

An early example of a merely financial separation of battery and the respective vehicle was the light electric vehicle Twizy, introduced to the European market by the French vehicle manufacturer Renault in 2012. [9] Available in three different performance models, all models were powered by the identical battery system, without variation of energy storage capacity or power output. The Twizy sales price did not include the battery pack, which was leased for a monthly fee that includes roadside assistance and a battery replacement guarantee. Battery replacements, however, could only be done by certified workshops. In 2020, the Twizy became available as a direct purchase in the UK, no longer slowing for the battery rental. The main challenge of such virtualized "Battery-as-a-Service" modes list that the physical and the financial life cycles of the battery and the vehicle need to be fully synchronized – otherwise one tends to restrict the lifecycle and therefore the potential revenues of the other to the minimum of both. In the times of first introducing the Twizy, battery lifecycle was expected to be much lower than that of the remaining vehicle; however, it has turned out that batteries may outlive their surrounding vehicles by a wide margin. The successor model of the Twizy debuted in 2024, in both a 2-passenger as well as commercial transport version under Renault's sub-brand Mobilize. In spite of intense evaluations during the development phase, a physical detachment of the battery for allowing battery swapping has not been announced yet, even though an earlier showcar with such capabilities was presented to the public. Also, only purchase prices including batteries have been announced, not providing for separate rental or leasing of the battery, thereby taking a step backwards from earlier attempts at "Battery-as-a-Service" models. Similar battery rental models were introduced for other electric vehicles, but have been cancelled by the time of this analysis.

The first large-scale attempt at "Battery-as-a-Service" including the physical separation of battery and vehicle was implemented by the California-based company "Better Place". While technical challenges were mostly overcome (see below), the business model proved unbalanced and ultimately led to the financial collapse of the venture. The business model that was implemented in Israel and Denmark was intended at selling the vehicles directly to private users and achieved recorded sales of merely 300 and 200 units, respectively. In Israel, 40 battery swapping stations were installed, each of which held up to 8 spare battery systems for replacement; in addition to swapping, the vehicles provided for wire-bound conductive charging. Users would buy vehicles including a battery system and would pay for swapped batteries through a surcharge on the contained energy. While the spare batteries were stored in the swapping stations, they were merely charged on the available grid, but did not incur any additional revenues from smart charging or other use. At the time, each of the battery backs represented a significant investment; a theoretical number of 320 spare battery packs held by the operating company in the swapping stations are suggested as incurring unexpected high capital cost and therefore ultimately causing the financial collapse of the company. [14]

A more recent example – and the only one actually using the term "Battery-as-a-Service" in their advertising – is the Chinese EV brand NIO, which was founded by William Li in 2014 under the name NextEV in China.

One of his most important technical advisors and manager of the R&D center in Munich was the former head of Ford Europe, Martin Leach. He was looking for ways to create a technological differentiator for the company and overcome the problems of high battery cost and long charging duration, and studied the potential of battery swapping extensively. Even the first exploratory vehicle – the high-performance sports car EP9 – featured two swappable battery packs, reducing the full charging time from 45 minutes for conductive charging to merely 8 minutes for a manual replacement with fully-charged batteries. All successively introduced passenger car models of NIO are compatible with a unified battery system of approximately 500 kg weight and provide nominal capacities of 70/75 kWh, 100 kWh, or 150 kWh (announced). For users to use the battery swapping model, they have to subscribe to a monthly rental contract for the battery over the period of their vehicle ownership – and are restricted to swapping batteries for ones of the same size (at least, in the current model of subscription). The 150 kWh-pack is only available for temporary rental after swapping at a surcharge. Users that opt to purchase the battery with the car are excluded from the battery swapping system. An automated battery swapping station is estimated to hold up to 21 battery systems at the same time and is announced to support up to 408 swapping processes per day. That relation implies that each battery slot will be cycled up to 19-times per day, or every 75 minutes – resulting in a theoretical charging rate of 0.8 C for each battery system, which is assumed to induce very little thermal and electric stress and therefore allow for extended battery life-time. NIO makes explicit reference to smart charging models applied in charging the spare batteries, allowing them to provide a limited number of free-of-charge battery swapping processes due low charging cost from direct energy-market purchase of electricity.

4.2 Technical Prerequisites

For mobile applications such as vehicles, Battery-as-a-Service models suffer from the necessity to carry the battery with the vehicle if it is used to provide propulsion energy during motion. Mixed use cases such as mobile – often ICE-powered - cranes who only at their point of deployment switch to electrical operation and get connected to a grid or (portable) battery are considered under the above use case of UPS rental services, as batteries can be placed "in the vicinity" of the application and connected through flexible wiring and standardized connectors. A related concept has recently started trials for railways, supporting electric freight locomotives with electric energy tender wagons carrying large-scale battery systems, inverters, charging connectors and thermal management systems. Should such tender wagons be operated independently of their respective locomotives and should the number of tenders be adapted in accordance with the weight of the train, length or profile of the relation, then this could in fact constitute a full "Battery-as-a-Service" model. Heavy-duty commercial vehicles in China are already routinely equipped with battery-swapping capabilities, mostly to avoid lengthy charging stops in uninterrupted 24/7-operating regimes. These battery systems are housed in large upright containers behind the driver's cabin, reducing the length of cargo space; battery exchange is done using overhead cranes and manually-operated connectors between battery system and vehicle.

The history of electric vehicle battery swapping had a first start around the turn of the 20th century, when electric taxi companies were operating networks of battery swapping stations in New York, Chicago and other major cities [. At the time, rechargeable batteries were only available in lead-acid chemistry, leading to penalizing charging times of several hours. Instead of keeping vehicles locked at charging stations, the free-standing vehicle hoods were completely removed and the box-shaped batteries swapped for charged ones by means of cranes or forklifts. This way, a full battery swap could be performed in 15 minutes. Similar systems have been in use with industrial applications such as electric forklifts – as long as they were equipped with lead-acid batteries. Paradoxically, the shift to more modern battery chemistries such as lithium-ion-based NMC or LFP and the ensuing reduction of charging times has led to the abandonment of Battery-as-a-Service models in most cases. In modern electric cars, however, it has become customary to place the traction battery system under the entirety of the main vehicle body in a flat, long and wide "mattress-shaped" aka "tuna-tin" container – instead of using the more upright packaging space of the combustion engine compartment. This has tempted engineers to integrate the battery system into the structure of the vehicle body, making any physical separation impossible. However, various attempts at fast separability of vehicle body and battery system have been made.

In the earliest, widely documented modern-era case, the startup company "Better Place" founded by a former

SAP board member had convinced Renault of modifying one of its electric vehicles for the rapid removal and replacement of the battery in order to allow for battery swapping. Although all technical challenges were overcome, the uniformness of the battery system, its interfaces to the vehicle and the absence of smart charging capabilities did not allow the establishment of a commercially viable “Battery-as-a-Service” business model. In a more recent attempt, the Chinese tech-startup NIO designed a number of vehicles around a common vehicle underbody, allowing for the rapid removal and replacement of the large and heavy underfloor battery system in purpose-built battery-swapping stations. However, two significant additional elements have been introduced with a view to supporting a fully-fledged Battery-as-a-Service business model. Firstly, while the battery systems are all identical in size and vehicle interface, they are available in three significantly different energy storage capacities, allowing for the adaptation of used capacity to the intended use; secondly, the vehicle storage in the battery swapping stations are equipped to allow for smart charging services. In addition, NIO has recently signed an MOU with other Chinese vehicle manufacturers and battery producers [12] to allow the application of their technical specifications to other battery systems, thus promoting a de-facto standardization – as one way of achieving technical interoperability.

4.3 Evaluation

For multi-track electric vehicles, both technical as well as economic challenges have to be overcome to create viable “Battery-as-a-Service” models – more precisely, numerous long-term habits supporting inefficient use of resources, energy and investment have to be rolled back. While battery technologies have advanced enough to make the “convenience argument” of decreasing charging times almost obsolete, other advantages such as smart charging of spare batteries and the adaptability of battery capacity to the individual use pattern have been widely overlooked. “Battery-as-a-Service” requires synchronous and interlocking adaptations of both the physical, technical side as well as of the legal and financial side of vehicle ownership and operations. Existing implementations have shown deficits on either side and therefore – expectedly – mostly collapsed. In personal vehicles – which, contrary to common perception, are not investments but rather highly expensive consumer goods – the marginal advantages of “Battery-as-a-Service” models may take more time to materialize. However, in low-margin commercial applications such as just-in-time goods transport, shared mobility, last-mile logistics, ports operations and agriculture, fully-fledged “Battery-as-a-Service” business models the right combination of technical implementation and financial scaling offer numerous advantages over conventional electrification approaches.

5 Synthesis and Outlook

Table 1: Synopsis of Battery-as-a-Service Business Models

	UPS Rental	LEV	EV	Ideal
Time-Based Fee	yes	yes	yes	yes
Energy-Based fee	no	no	yes	yes
Inter-Operability	adaptation	standardization	no	interfaces
Scalability	pre-use	no/ limited	limited	in-use
Smart Charging	in depot	no	in stations	in application

“Battery-as-a-Service” denotes a variety of different business models, which all have in common that the rechargeable battery is both physically as well as financially detached from the appliance (mostly vehicle) it is intended to power. In most cases, in-use swapping of batteries in leu of cable-based charging is also an element of the model; more advanced models allow the adaptation of charging capacity to the intended use cycle. Grid-serving “smart” functionalities are mostly provided only when batteries are stationary and stored for charging, but nor during their use in the appliance. An ideal application would provide these functionalities also when the battery is employed in the application, allowing for additional revenue potential.

5.1 Time-Based Fee

Since battery systems still constitute a major investment, any Battery-as-a-Service model will have to account for the expected temporal lifespan of the battery. At the time of establishing the concept, high-performance battery lifecycles were estimated at around 300 full charge cycles, quickly extending to 3000 or more expected cycles. Latest announcements suggest new battery chemistries with a technical capacity of 10,000 or more full charging cycles, extending the life span of a battery system far beyond that of any light vehicle or systematic – adding even more reason to implement the financial separation of battery system and technical application. One of the main commercial advantages of BaaS models is the adaptation of battery capacity to the required use pattern. Since most applications are used far below technical capacity, the installed battery capacity will often be much lower than the full nominal capacity, further reducing cost. While the current full-cycle cost for storing 1 kWh of energy in a battery system is estimated at around 0.08 €, it is to be expected that the time-based element of Battery-as-a-Service fees will decrease further over time.

5.2 Energy-Based Fee

One of the main characteristics of Battery-as-a-Service models is the technical separation of the battery system and the electrical application, allowing for the charging of the battery system independent of operating times of the application. Especially in high-intensity use cases, that will allow for slower and better-controlled charging processes, rendering several advantages: the reduced charging C rate will reduce the thermal stress and therefore chemical decay of the battery prolonging its useful lifetime; slower charging also implies lower charging power, reducing stress on the supplying grid and reducing power-based electricity fees. Using advanced smart charging services during the prolonged dwelling time of a separated battery system in a chargeable storage, net charging costs may be reduced significantly by leveraging spot-market price variations, including occasional negative prices during energy surplus. It is therefore to be expected that the energy-based fee of Battery-as-a-Service models will be reduced significantly over time, further enhancing the advantage over conventional charging models.

5.3 Inter-Operability

One of the key prerequisites for Battery-as-a-Service models is of course the seamless connection and integration of the battery system with the electric application on the one side and the energy supply on the other. Both connections require not only physical and electrical matching but also analogue and digital communication, safety and security integration, risk surveillance and mitigation, and others. In the case of stationary applications and/or connected storage of battery systems, such interoperability can be supported through flexible, multi-sided connectors and adaptors, inducing corresponding efforts for specification and adaptation in every different case. Such model will only work when coupling and de-coupling of the battery system and the application occurs comparatively rarely compared to the active deployment period. In the evaluated cases of merely financial BaaS models, such re-matching is avoided entirely. In cases with very frequent and short-term deployment periods, the coupling processes must be highly efficient and adaptive. In the evaluated cases, the BaaS operators have defined proprietary physical and functional interfaces (form factors, plugs and sockets), however excluding any other systems and thereby creating highly “fenced” islands of interoperability. In an ideal case, inter-operability between charging infrastructure, battery system and electrical application would be highly adaptable, flexible and self-configuring within the widest-possible technical border conditions.

5.4 Scalability

In stationary applications – such as UPS – it is a required part of the Battery-as-a-Service proposition to specify the required size, power and capabilities of the battery system precisely to the individual application and budget. In some evaluated cases such as the Gogoro e-scooters, limited adaptability of battery volume is provided by means of modular battery packs, allowing the user to add optional capacity at an additional cost for an individual use cycle. Most mobile applications – especially in road-going vehicles - simply install the technical maximum in capacity, power and specification of a battery system; since it is usually fixed-mounted, it increases the cost – and price – of such applications unnecessarily, as most use cases require much lower specification and performance. This has multiple adverse effects: more expensive applications reduce market demand and therefore diminish the potential scale effects for lowering production cost; over-specified battery systems make applications unnecessarily heavy both through the direct addition of weight but also requirements on overall rigidity and sturdiness; even factory layouts and production logistics require significant upgrades when products become excessively heavy. In an ideal BaaS scenario, battery capacity would be adapted for each use cycle both physically and financially, leading to a significant reduction of employed capacity over a fleet of electric applications; if such scalable systems would be interoperable across multiple sectors, overall efficiencies could be increased even more – leading to faster adaptation of electric applications, more controllable growth of electric energy demand, and in turn higher investments on both the generation as well as consumption side.

5.5 Smart Charging

While the focus of this evaluation is on the electrification of consumer side of energy – namely, electric installations and vehicles – the decarbonization of the entire economy also requires the electrification of energy generation and supply. Some increasingly relevant sources of carbon-free electric power such as solar, tidal and wind power, however, suffer from irregular production patterns and cannot be directly aligned with consumption. Therefore – if extreme overcapacity and subsequent underutilization is to be avoided – generated electric power needs to be stored temporarily. In a process generally referred to as “Sector Convergence”, the energy sector providing for the production and distribution of electrical power increasingly interacts with their consumer sectors and provides access to internal market mechanisms and compensation schemes. In this context, charging processes that consider the power generation side in their set- up and performance are called “smart charging” and may range from simple delays of charging process with respect to power availability or energy price signals to highly sophisticated bidirectional charging schemes with mutual monetary compensation. In the context of Battery-as-a-Service business models, such cross-sectoral monetary compensation schemes represent an increasingly important component of the revenue model, especially for unused replacement batteries waiting for their next active deployment, and therefore not receiving direct compensation. However, smart charging schemes could also be applied to in-use batteries for additional revenue generation, while connected to a local or wide-area power grid.

5.6 Outlook

“Battery-as-a-Service” business models face a number of challenges in their implementation, as a specific commercial as well as technical prerequisites have to be met in order to build a sustainable and operational system. Especially the physical separation between electric device and integrated battery system by ways of “battery swapping” poses significant technical challenges and faces wide-spread skepticism and scrutiny. Of the identified core elements of a BaaS business model, this aspect certainly poses the biggest challenge, while the adaptation of battery capacity to individual use cases constitutes the greatest advantage and has the greatest potential for motivating further exploration of the model.

I hope that this synopsis will be instrumental in clarifying and aligning ongoing efforts towards developing more sustainable, financially and physically efficient models for the deployment of rechargeable batteries, as one of the key technologies for the ongoing decarbonization of our technology-driven societies with the ultimate goal of preserving the natural and cultural foundations of the World as we know it.

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I would like to thank Philipp Rosengarten and Peter Marchl for co-founding the company Clean Energy Global GmbH with me in 2016. Based on a simple but brilliant idea of how to swap scalable battery packs from underneath an electric vehicle, we developed a complete understanding of what it takes to establish an economically valid Battery-as-a-Service business model. The term itself was actually coined by the greentech investor Gerard Reid during a casual visit to our small booth at Hannover Messe 2019. The company is still working towards a major breakthrough under Philipp's diligent management.

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8 Presenter Biography

Christoph Stürmer is a strategic advisor to startups, SME companies and industry associations in the automotive, mobility and e-mobility sectors, and a lecturer at Aalen University.
He graduated in Economics and Philosophy at the University of Heidelberg, Germany and started his automotive career as a product manager and strategic planner for Mercedes-Benz Cars. After several management positions at IHS Automotive (today S&P Mobility), he led the automotive think tank PwC Autofacts®, while founding a startup for providing Battery-as-a-Service. He then joined Vindelici Advisors as Head of the Automotive Practice, followed by a tenure as Director at the global EV charging association CharIN.

9 Appendix: Glossary

- Application: In a technical context, an "application" can denote two different things:
  - An "application" is a type of technical device that makes use of a certain technology; in this case, an electrical device (such as car, LMT, machine, UPS) which is powered by internal or external battery systems.
  - An "application" is a type of technical activity that makes use of a certain technology; in this case, the movement or transport of people and goods (such as personal transport, public mobility, commercial logistics) or other electrically-powered operations such as industrial production, service, maintenance, repair, etc. in which electric power is delivered by internal or external battery systems.
- Battery: a "battery" as denoted in this paper is a device for the storage of electrical energy in chemical substances, mostly based on lithium-ion exchange but also lead-acid or other chemistries. For practical purposes, the batteries considered here are "secondary batteries" allowing for multiple charging and discharging cycles; these batteries are also called "accumulators". The individual battery is often specified as a "battery cell" and is available in different sizes, geometries and electrical properties such as voltage, power output or energy capacity.
- Battery System: a "battery system" is a technical device for the controlled storage of electric power, comprised of battery cells, a battery management system (BMS), wiring, sensors and connectors as well as a casing enclosing the electrical components, often with integrated thermal management components. Battery systems can vary widely in size, shape and capacity. In an automotive context, a battery system is sometimes referred to as a "battery pack".
- (Battery) Swapping: The process of "battery swapping" refers to the rapid exchange of battery systems in an electric device on the initiative of the user or owner of the device. In the most basic sense, battery swapping is understood as an alternative to conductive battery charging, by exchanging an electrically depleted battery system against a fully charged one of the same specification.
- C-Rate: While individual charging cycles are characterized by their SOD to SOC range, the relative and absolute power of charging/ discharging determines the duration of the charging process. As battery systems can vary significantly in both electrical as well as physical characteristics, the rate of (dis-)charge relative to the nominal power capacity of the battery system has become a popular measure for estimating the relative intensity of the charging process and the probable technical decay ("wear") it can inflict on the battery. Using the simple calculation $C = p/c$ with p being the electrical power in kW and c being the nominal capacity in kWh, the charging a battery of $c = 100$ kWh at a rate of 100 kW would render a C-rate of 1/h, i.e. a full (dis-charge) within 1 hour aka 60 minutes. It is generally assumed that C-rates below 1 create little battery wear, while higher C-rates may create both electrical, thermal as well as chemical stress or damage. However, certain battery cell types and chemical compositions are better suited for high C-rates (up to C=10, i.e. a full charge within 6 minutes).
- (Charging) Cycle: A "charging cycle" denotes the process of one charge and consecutive equivalent

discharge of a battery system, irrespective of the amount of energy deployed. In a technical context, a “cycle” often denotes a “full cycle”, where the battery is fully charged from a status of complete discharge, and then completely discharged again.

- kVA: The physical units kVA is used to denote electric power in thousand Volt-Ampere. In the connection of this study, the unit is also used to denote the power delivery capability of a battery or battery system. Different power delivery capabilities are reported, such as “peak” (maximum delivery), “nominal” (permanent delivery), or “cutoff” (minimum delivery).
- kWh: The physical unit kWh is used to denote electric energy in 1000 Watt-hours. In the connection of this study, the unit is also used to denote the energy storage capability of a battery or battery system, often referred to as “battery capacity”.
- Life Cycle: The nominal “life cycle” of a battery system is often indicated as the number of full charging cycles the battery can perform until the degradation of the battery cells has reduced the SOH to 80% of original nominal capacity or below. It should be noted that due to chemical properties of battery cells, the decline of SOH can accelerate rapidly beyond a threshold, showing non-linear development.
- Second-Life: The initial period of battery use until the first minimum SOH threshold (e.g., 80% of nominal capacity) is reached is often referred to as “First Life”. Following that period, batteries or battery systems can still be deployed in other applications with less power and/or capacity requirements after re-purposing or re-manufacturing. That secondary deployment is often called “Second Life” and leads up to the final dismantling and recycling phases.
- Smart Charging: The charging of battery systems increases their State-of-Charge to a desired level, mostly between 80 and 100% of nominal capacity. Any charging process that is not merely started at full power in the moment of connecting to the grid but is controlled or regulated to meet auxiliary requirements is referred to as “smart”. In the simplest case, the charging process may be managed to avoid temporary overloading of the charging grid, either through temporary variation of the start and end time of the charging process, or limiting of the actual power available for charging, in so-called “V1G” models. More sophisticated “V2X” models also allow for controlled, partial discharging of the battery in favor of local energy demand, either for domestic (vehicle-to-home, “V2H”) or industrial (vehicle-to-power, “V2P”) energy management purposes, or for support of the general electricity grid (vehicle-to-grid, “V2G”).
- SOC: The “State Of Charge” denotes the maximum share of nominal battery capacity used for electric energy storage. While batteries can technically support charging up to 100% SOC, normal operations would limit the regularly attained SOC to 80% - 90%, especially when long storage times are required.
- SOD: The “State Of Discharge” denotes the minimum share of nominal battery capacity used for electric energy storage. While batteries can technically support discharging down to 0% SOC, normal operations would limit the regularly attained SOD to 10% - 20%, especially when long storage times are required.
- SOH: Numerous definitions exist for “State Of Health” of a battery system. Most commonly, it refers to the share of nominal battery capacity available for actual charging and discharging, as batteries tend to lose some of that capacity over time through different chemical and physical ageing processes within individual battery cells. Other definitions refer to the remaining lifetime of the battery system, either until a certain SOC threshold is reached, or full electrical failure is to be expected. It should be noted that a direct, internal measurement of SOH is not possible but requires dedicated tests using external equipment. However, some BMS calculate SOH estimates based on electrical and environmental data collected during the use of the battery system. Alternative definitions include the SOCE (“State of Certified Charge”) according to United Nations Global Technical Regulation No. 22 (“United Nations Global Technical Regulation on In-vehicle Battery Durability for Electrified Vehicles”) as required by the EU Battery Regulation (2023/1542) for documentation in the Battery Passport from February 18, 2027, onwards.