WHITE PAPER

The Value of a Step-Change Increase in Battery Energy Density for Consumer Mobile Device Satisfaction

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Executive Summary

The first commercial lithium-ion (Li-ion) battery had an energy density just less than twice that of the nickel-cadmium and nickel metal-hydride batteries it replaced. Without this step-change increase in energy density, the brick-size cell phone of the 1980s would never have evolved to today's sleek, sophisticated smartphones. But since its introduction, the Li-ion battery has only increased its energy density an average of 4.36% annually.

Survey after survey has revealed that the number one consumer wish for their mobile devices is better battery life. But despite their displeasure, consumers continue to purchase over a billion mobile devices each year. Closer examination of battery life as a factor in overall consumer satisfaction indicates that it is more nuanced.

Battery life is first a threshold and then a graduated factor in overall consumer satisfaction. There is a minimum time between required charging of a device that consumers find acceptable. Below this threshold, consumers will not adopt and use a device en masse. However, above this threshold, battery life competes with user experience and device functionality for overall consumer satisfaction.

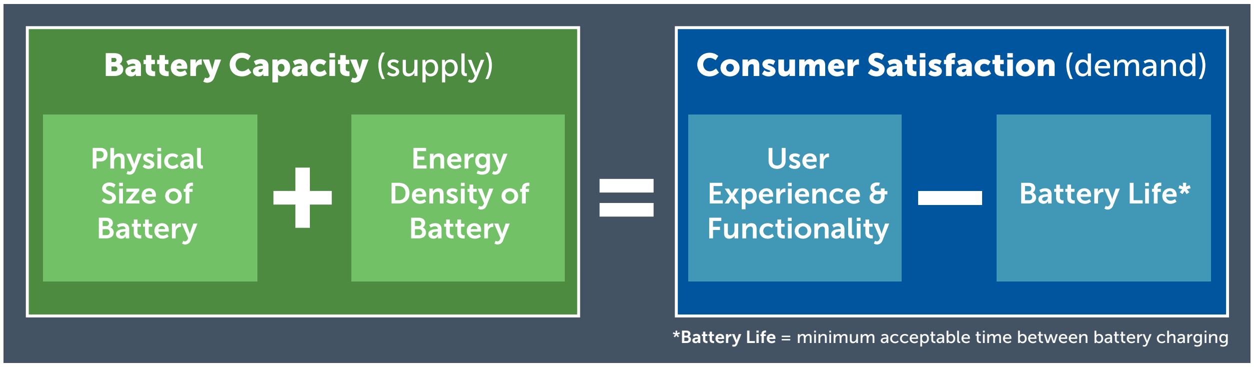
The simplest way to increase battery energy capacity is to increase battery size. But with consumer mobile devices, there is little latitude to significantly increase the physical size of the battery. The form factor of smartphones, smartwatches, and smart glasses are largely established by user ergonomics and preferences. And as the consumer mobile device revolution evolves more towards wearable devices during the 2020s, battery size is more likely to decrease than increase.

The other way to increase battery energy capacity is to increase its energy density. Enovix has developed an advanced Li-ion battery that uses silicon as the only active lithium cycling material (i.e., 100% active silicon) in the anode to significantly increase energy density and maintain high cycle life. The Enovix 3D Silicon™ Lithium-ion Battery provides a step-change increase in energy density. This empowers designers and producers in all dimensions of the value equation for consumer mobile device satisfaction.

They can utilize a significant increase in energy density to design devices that meet the minimum battery life threshold required by consumers for mass-market adoption of next-generation mobile devices. Once that threshold is achieved, they can use the energy density advantage to create differentiated user experiences and device functionality, or to decrease physical battery size and weight in order to compete based on device form factor and design, or to do both. As it was 30 years ago, continued innovation leading to greater consumer satisfaction is the ultimate value of a step-change increase in battery energy density for mobile devices.

Figure 1

Battery capacity value equation for consumer mobile device satisfaction



(source: Enovix Corporation)

The lithium-ion (Li-ion) battery powers billions of mobile devices around the world every day.[1] But it also presents limitations for user experience, device functionality, and, ultimately, overall consumer satisfaction. A step-change increase in battery energy density is required for continued innovation and to keep the consumer mobile device revolution on track for the 2020s. The **Figure 1** equation shows the relationship between battery capacity (supply) and consumer satisfaction (demand). Examination of this equation involves quantitative and qualitative analysis.

Battery Life

As most often used in relationship to a mobile device, battery life is a misnomer. Literally, battery life is how long a battery will function through periodic charge and discharge cycles before its performance degrades to an unacceptable level. For mobile devices, this is most often measured as how many times a battery can be cycled to a full depth of discharge and fully recharged before it degrades to 80% of its initial capacity. This is also called cycle life.

However, battery life is generally used to describe the time a mobile device will function before the battery must be recharged, and it is a point of great dissatisfaction with most consumers. A J.D. Power 2012 Customer Satisfaction Study first noted that, "satisfaction with battery performance is by far the least satisfying aspect of smartphones."[2] Since then, survey after survey has revealed that the number one consumer wish for their mobile devices is better battery life.[3]

Despite their displeasure, consumers continue to purchase over a billion smartphones and other mobile devices each year.[4] Closer examination of battery life as a factor in overall consumer satisfaction indicates that it is more nuanced. It appears that battery life is first a threshold and then a graduated factor in overall consumer satisfaction. In other words, there is a minimum time between required charging of a device that consumers find acceptable. Below this threshold, consumers will not adopt and use a device en masse. However, above this threshold, battery life competes with user experience and device functionality for overall consumer satisfaction.

> A step-change increase in battery energy density is required for continued innovation and to keep the consumer mobile device revolution on track for the coming decade.

Therefore, better battery life alone does not necessarily equate to higher consumer satisfaction. A comparison among U.S. smartphone customers by the American Customer Satisfaction Index (ACSI) shows the Apple brand with the highest overall satisfaction rating of 82 in 2020,[5] although the battery life of the iPhone 11 is only 11:16 (hours:minutes) and that of the iPhone 11 Pro Max is only slightly better at 11:54. Conversely, the Moto G Power is top rated for battery life at 16:10.[6] But at 77, Motorola has the lowest overall satisfaction rating among major smartphone brands.[7]

On the other hand, mobile device producers understand that dropping below a consumer expected threshold for battery life can adversely affect mobile device adoption and mass-market use. Evolution of the Apple watch is an example of how insufficient battery capacity can adversely affect battery life, functionality, and, ultimately, product adoption and consumer satisfaction.

When Apple introduced its second-generation smart watch in 2016, it did not include an expected direct cellular network connection feature because, as Bloomberg reported, “current cellular chips consume too much battery life, reducing the product’s effectiveness and limiting user appeal.” Apple had to delay adding functionality that would untether the Watch from the iPhone because of insufficient battery capacity.[8] Later that year International Data Corporation (IDC), a global provider of market intelligence, reported that battery-life frustration was one factor stalling smartwatch market adoption beyond early enthusiasts.[9]

When the Apple Watch Series 3 was introduced a year later, in 2017, a direct cellular network connection feature was included. But some reviews of Apple Watch performance were negative. Joanna Stern’s review for The Wall Street Journal was representative: “You’re lucky if the battery allows you to roam on cellular for longer than half a day—especially if you’re making calls ... Unless you plan to carry around a 5-pound backup battery in your bag, living a full day with just the Apple Watch isn’t happening.”[10]

A year later, in 2018, when the Apple Watch 4 was introduced, Ms. Stern had changed her tune, “The Series 4 feels like it has been through a needed maturation process, with refinements to the screen, the battery, the cellular connectivity, and more.” A combination of increased battery capacity and energy-efficient chips improved user experience and functionality (display and connectivity) as well as battery life[11]—a win-win.

The following year, in 2019, she described how battery performance could enhance a basic smartwatch feature. “With the always-on display, I was able to make it through a full day—7 a.m. to 11 p.m.—with just under 10% battery left. But when I disabled the always-on feature in settings, I had 30% remaining—just like with my Series 4.”[12] Better battery performance can improve consumer satisfaction by providing a choice of greater functionality or longer battery life, but only after it meets minimum battery life expectations.

> For devices such as smartphones and smartwatches, consumer expectation is that battery life will be sufficient to get them through a normal day.

Regarding battery life, consumers would prefer their mobile devices to perform for days or weeks between charging, and some fitness trackers do.[13] But, for devices with greater functionality, such as smartphones and smartwatches, there is a consumer expectation that battery life must be sufficient to get them through a normal day.

User Experience and Functionality

When a new product delivers a better user experience with functionality that consumers prefer, it often disrupts the market. And that produces winners and losers. This dynamic can be particularity fierce in fast-moving markets such as mobile devices. For example, in Q4 2006, the top 5 producers of smart-mobile devices were Nokia, RIM (Research in Motion: Blackberry brand), Motorola, Palm, and Sony Ericsson, in that order. Samsung was lumped in the bottom quintile with “Others,” and Apple would not enter the market with its iPhone until the following year.[14]

By 2010, smartphone market disruption was well underway. While Nokia and RIM maintained first and second place in the market, both had lost share. Three years after introducing the iPhone, Apple was less than one percentage point behind RIM in market share, and Samsung was growing quickly. Motorola, Palm and Sony Ericsson had fallen out of the top 5.[15]

By 2016, Samsung and Apple had firmly established themselves as the dominant market leaders, and were clearly the big winners. The top 5 smartphone producers from a decade earlier had sunk to the bottom of the marketplace, and their brands and devices had become, essentially, irrelevant.[16] They missed the shift to touch screens and expanded functionality that increased customer satisfaction. As a result, they were the big losers.

The functionality of popular mobile devices, including smartphones and smartwatches, has increased significantly over the past decade. The most common functional elements are hardware components (CPU, GPU, display, etc.), signaling modules for connectivity (Wi-Fi, cellular network, Bluetooth and GPS), software (operating system and applications), and consumer usage patterns (calling, texting, gaming, taking photos and videos, music and video playback, etc.).[17]

Today, the CPU and GPU, display, signaling modules (connectivity), and applications such as gaming and video playback consume the majority of the battery's energy in a mobile device.[18] However, emerging technologies that promise a better user experience and increased functionality will place an even heavier burden on the battery.

For example, 5G cellular networks promise an improved user experience due to much faster data transmission and lower latency. It will also increase network capacity and relieve the pressure on loaded 4G networks. 5G adoption is projected to be the fastest ever for a new wireless generation, generating six times more unit shipments than previous record holder LTE, over a similar timeframe.[19]

But there will initially be a price to pay in battery life. Global testers from c|net noticed using 5G on phones like the Moto Z3, Galaxy S10 5G, and LG V50 seemed to tap their battery reserves faster than 4G networks. And 5G smartphones may be larger than 4G models, in part to accommodate larger batteries, yet still suffer from shorter battery life. For example, c|net also reported that "...the [Samsung] S10 5G has a slightly larger screen and battery than the Galaxy S10 Plus (6.7-inch and 4,500 mAh versus 6.1-inch and 4,100 mAh)," but in a test, "The S10 5G [battery life] was on a trajectory to last far less."[20]

In addition, movement of AI from the cloud, where it has traditionally been deployed, to smart devices will improve functionality and user experience. The computation power of AI algorithms has increased 300,000 times between 2012 and 2019—doubling every three-and-a-half months. The cloud has been a logical place for AI because it provides massively scaled computational power and very cheap memory and storage.[21]

But cloud-based AI has its issues, including latency—as data moves to the cloud for processing and the results are transmitted back over the network to a mobile device—and data security. On-device AI results in faster performance and response time, lower latency and improved security by retaining data on the device. Gartner predicts that by 2022, 80% of smartphones shipped will have on-device AI capabilities, up from 10% in 2017.[22] But on-device AI will compete with the CPU, GPU, and display for battery life in mobile devices.[23]

The technology with the greatest potential for major market disruption over the next decade is augmented reality (AR). The AR market is projected to grow from under $3.5 billion (US) in 2017 to over $192 billion in 2025.[24] According to Apple CEO, Tim Cook, AR represents a major new mobile platform. "I regard it as a big idea like the smartphone. I think AR is that big, it's huge."[25] Apple is not the only company that thinks AR is huge. According to The Information, Facebook, Microsoft, and Snap have major development programs. If companies can make the technology reliable and lightweight enough, AR could eventually replace smartphones as the primary mobile platform.[26]

> According to Apple CEO, Tim Cook, augmented reality (AR) represents a major new mobile platform. "I regard it as a big idea like the smartphone. I think AR is that big, it's huge.

For this to occur, AR glasses must get smaller, lighter, and more powerful. The lenses that display digital imagery and information in front of people's eyes will need to be high quality while also sufficiently small for a comfortable fit. Broad access to fast 5G mobile networks is considered a critical enabling technology for AR to grow its presence in both consumer and industrial markets. And Li-ion batteries will need to provide more energy capacity in a small-size, lightweight format. Most reports indicate that AR glasses meeting these requirements may be available in 2022 or, more likely, in 2023.[27]

To date, no producer has been able to deliver smart glasses (a precursor to AR glasses) that have gained consumer acceptance beyond early enthusiasts. The user experience and functionality of higher profile products—Google Glass 2, introduced in 2017, and Spectacle 3 from Snap, introduced in 2020—have proved suboptimal for widespread consumer adoption. Reviews of both note the limitations of battery performance as a major issue.

Reviewing Google Glass 2, Matt Swider, of TechRadar, says, "Google's official estimate for the Glass' battery life is 'one day of typical use.' Features like video recording, however, can drain the battery even more quickly, the company warns. Avoiding these more intensive features, I found my Google Glass battery to last between three and five hours depending on how many hands-free photos I was taking in that time span. Recording a video wiped the battery out in less than an hour after continuously shooting. To conserve battery life as much as humanly or cyborgly possible, I turned off head wake up, on-head detection and Wink for picture. I also carried around an external high-capacity battery pack in my pocket with a USB cable running to the micro USB port. I don't suggest this look."[28]

For now, Goggle has turned its attention to business applications with its Google Glass Enterprise Edition 2, primarily targeting jobs in construction and on factory floors as well as in the medical field. Google emphasizes that Google Glass Enterprise is not designed for everyday consumer use.[29]

Reviewing Spectacle 3, Lexy Savvides, of c|net, says, "The battery life on Spectacles isn't great. Snap says you will get about 70 snaps from each charge, plus enough juice to sync to Snapchat. I found that I managed to get 75 video snaps out of the glasses (equivalent to 12 minutes, 30 seconds of video) and transfer them to my phone before I had to recharge. Not great if you were using these all day at an outdoor festival, for example."[30]

User experience, functionality, and battery life are the demand side of the equation. Collectively, they are the elements that determine consumer satisfaction.

Physical Battery Size

The simplest way to increase battery energy capacity is to increase battery size. But with consumer mobile devices, there is little latitude to significantly increase the size of the battery. The form factor of smartphones, smartwatches, and smart glasses are largely established by user ergonomics and preferences.

With smartphones, designers have been able to increase battery size behind larger displays, which appeals to users that watch videos on their smartphones.[31] But the increased energy supply of the larger battery primarily supports the increased energy demands of the display, without adding additional functionality or significantly increasing battery life.

A comparison of display size, functionality and battery life between the iPhone 11 Pro and the iPhone 11 Pro Max demonstrates this. The display size of an iPhone 11 Pro is 5.8 inches and the display size of an iPhone 11 Pro Max is 6.5 inches, otherwise functionality is identical,[32] while the battery life of the iPhone 11 is 11:16 (hours:minutes) and that of the iPhone 11 Pro Max is only about 3.5% higher at 11:54.[33] In addition, a majority of consumers have recently begun to complain that smartphones are getting too big, and it's unlikely that the trend will continue.[34]

The form factor of smartphones, smartwatches, and smart glasses are largely established by user ergonomics and preferences.

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Smartwatches offer even less latitude to increase battery size than smartphones. The display size of smartwatches from Apple and Samsung with cellular connectivity to make calls, send texts, stream music, download apps, and do anything else that requires an internet connection are about 1.6 inches. These smartwatches with full-color, smartphone-like displays are estimated to last about 18 to 24 hours on a single charge.[35] The form factor (height, width, and thickness) of smartwatches is well established, and there is very little latitude to significantly increase battery size.

AR glasses will most likely follow a path to the consumer market similar to that taken by smartwatches. The first round of viable consumer AR glasses probably won't be stand alone. Instead they will be tethered to a smartphone or other device that provides most of the computing and battery power.[36] But for AR glasses to achieve mass-market adoption by consumers, they must get smaller, lighter, and more powerful.[37] Consumers will want to wear standard-size glasses in public, not over-sized goggles, and this will greatly limit onboard battery size and weight.

It is more likely that the Li-ion batteries in wearable mobile devices will need to be smaller and lighter, rather than bigger and heavier. And if batteries for wearable devices can't realistically get much bigger, then they must get significantly better.

Battery Energy Density

It took a step-change increase in battery energy density to enable the mobile revolution. Sony Corporation developed and commercialized the first Li-ion battery in 1991 for its handheld camcorder—a harbinger of many power-hungry portable electronic devices to come.[38] The first commercial Li-ion battery had an energy density of about 200 Watt-hours per liter (Wh/l)[39]—a little less than twice the energy density of the nickel-cadmium (NiCd) and nickel metal-hydride (NiMH) batteries it replaced. Without this innovation, the brick-size Motorola DynaTAC cell phone of the 1980s would never have evolved to today's sleek, sophisticated smartphones from Apple and Samsung.[40]

But since the Li-ion battery was introduced, energy density has only increased an average of 4.36% annually. For the past decade, smartphone[41] and smartwatch[42] producers have compensated for low energy density by designing more energy-efficient semiconductor components. But, improving chip efficiency alone will not be sufficient to meet consumer expectations during the 2020s.

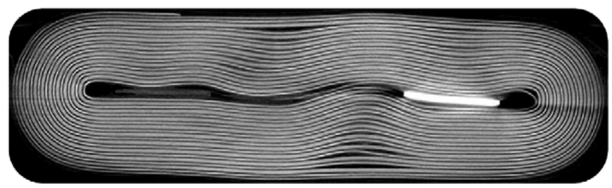
One method to achieve a significant advancement in battery energy density could come from replacing the graphite anode in today's Li-ion battery with one made of silicon.[43] But this does not appear practical with conventional Li-ion cell architecture.

The vast majority of Li-ion batteries use a graphite anode, which is carbon in a crystalline form.[44] A graphite anode absorbs lithium ions when the battery is charging and releases them back into the electrolyte when the battery is discharging. At the anode, lithium (Li) combines with graphite (C) at a one-to-six (1:6) ratio (LiC_6). This gives graphite a theoretical specific capacity of about 372 milliamp-hours per gram (mAh/g).[45] Researchers have long known that a silicon anode could significantly increase the energy density of a conventional Li-ion battery.[46] Silicon (Si) is an attractive anode material because it forms a $Li_{15}Si_4$ alloy. Its increased ratio of Li to Si bonding gives silicon a theoretical specific capacity of about 3,579 mAh/g, over 9 times that of graphite.[47] Volumetrically, lithiated silicon occupies 3 times less volume than lithiated graphite in a charged state (2,194 Ah/l versus 719 Ah/l).[48]

Figure 2 shows a photomicrograph cross-section of conventional Li-ion cell architecture, where electrodes and separators are wound to fit into a rectangular metal case or a polymer pouch. Unlike a graphite anode, one that is predominately silicon can cause a conventional Li-ion cell to experience a large volume expansion upon lithiation (charge). During delithiation (discharge), the cell shrinks. As it does, silicon particles discharge non-uniformly, which causes them to electrically disconnect from current collectors, over-discharge, and pulverize. As particles pulverize through repeated discharge cycles, new silicon surfaces open, which causes solid-electrolyte interphase (SEI) to form, and this results in accelerated Li-ion loss.[49] Therefore, a conventional Li-ion cell with a 100% active silicon anode has a very short cycle life, often less than 100 full-depth of discharge cycles to 80% capacity.

Figure 2

Conventional Li-ion cell architecture

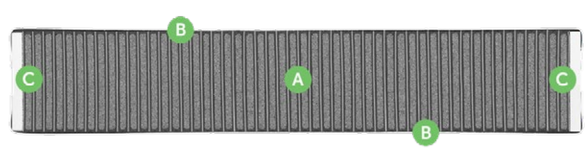


Photomicrograph cross-section of a conventional wound Li-ion cell shows electrodes and separators wound and flattened (source: Journal of The Electrochemical Society)

Figure 3 is a photomicrograph cross-section of an Enovix 3D cell. Electrodes and separators are laser patterned and stacked side-by-side (A) and enclosed top and bottom with thin (50 micron), lightweight stainless-steel constraints (B) that hold stainless-steel end caps (C) in place. The end caps apply sufficient restraining force on the electrode stack to contain silicon expansion within the cell and limit external swelling during charge cycles. Typical swelling of an Enovix 3D cell after 500 cycles is less than 2%.

Figure 3

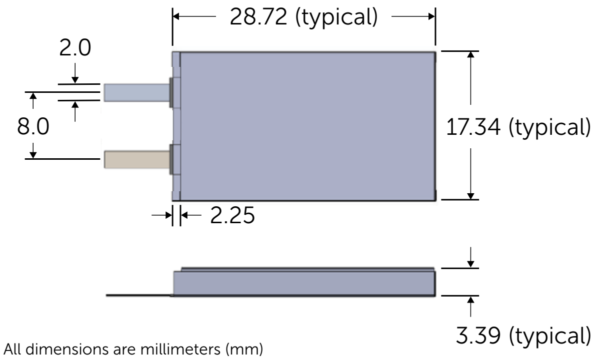
Enovix 3D cell architecture



Photomicrograph cross-section of an Enovix 3D cell shows laser-patterned electrodes and separators vertically stacked within a stainless-steel constraint (source: Enovix Corporation)

Figure 4

Wearable Device Format Enovix 3D Silicon Lithium-ion Battery



All dimensions are millimeters (mm)

Capacity[1]	
Typical	337 mAh
Energy Density (typical)	
Volumetric	722 Wh/l
Cycle Life (minimum cycles)[2]	
25°C to 80% capacity retention	500 cycles
45°C to 60% capacity retention	500 cycles
Cell Voltage	
Charge cut-off	4.35 V
Discharge cut-off	2.70 V
Average discharge[1]	3.62 V

[1]Test condition: 0.1C discharge rate
[2]Test condition: 0.7C charge to 4.35 V with 0.04C cutoff, 0.5C discharge to 2.7 V

(source: Enovix Model EX1-341729A)

A Battery for the Mobile Future

The demand for Li-ion battery capacity for consumer electronics, which includes portable computers, smartphones, tablets, wearable devices, and other mobile electronic devices, is projected to nearly double between 2020 and 2030.[50] For example, in 2020, shipments of wearable devices for the full year grew 28.4% to 444.7 million units.[51] In addition, battery capacity is seen as an important factor in the large-scale adoption of wearable devices, which have significantly less available volume to house batteries as compared to, for example, smartphones, tablets, and other mobile electronic devices.[52] As such, a step-change increase in battery energy density would be fundamental to the continued innovation of mobile devices, in general, and wearable devices, in particular.

Figure 4 shows a photograph, package dimensions, and key specifications of an Enovix 3D Silicon Lithium-ion Battery for wearable devices. **Figure 5** compares the volumetric energy density and package dimensions of the Enovix battery with those of the Li-ion battery in an Apple Watch Series 6. The 49% greater energy density of the Enovix battery is a step-change increase that can help power continued innovation leading to greater consumer satisfaction.

Figure 5

Comparison of Smartwatch Lithium-ion Batteries[53]

	Enovix 3D Silicon Lithium-ion Battery	Apple Watch Series 6 (44mm) Battery
Volumetric Energy Density	722 Wh/l	485 Wh/l
X Dimension	28.72 mm	27 mm
Y Dimension	17.34 mm	20 mm
Z Dimension	3.39 mm	4.6 mm

(source: Enovix Model EX1-341729A and estimated specifications from cell markings on Apple Watch Series 6 battery)

Conclusion

The first commercial Li-ion battery had an energy density of about 200 Wh/l when introduced in 1991—about twice the energy density of the NiCd and NiMH batteries it replaced. Without a step-change increase in energy density, the brick-size cell phone of the 1980s would never have evolved to today's sleek, sophisticated smartphones. But since its introduction, the Li-ion battery has only increased its energy density an average of 4.36% annually.

As the consumer mobile device revolution evolves from smartphones to wearable devices over the coming decade, another step-change increase in Li-ion battery energy density is required. A Li-ion battery with a 100% active silicon anode can provide this increase in energy density and empower designers and producers in all dimensions of the value equation for consumer mobile device satisfaction.

Designers and producers can initially utilize the increase in energy density to design devices that meet the minimum battery life threshold required by consumers to widely adopt new wearable devices. Once that threshold is achieved, they can use an energy density advantage to create differentiated user experiences and device functionality, or to decrease physical battery size and weight in order to compete based on device form factor and design, or they can do both. As it was nearly 30 years ago, continued innovation leading to greater consumer satisfaction is the ultimate value of a step-change increase in battery energy density for mobile devices.

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53 Enovix Model EX-1-341729A vs Apple Watch Series 6 (44mm), Battery Model A2327 nominal energy density; the Apple Watch Series 6 energy density is an estimate, estimated to be 3% greater than the minimum energy density, calculated from the battery energy capacity ("1.17 Whr") and dimensions ("462027") printed on an actual Apple Watch Series 6 (44 mm) battery.

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Enovix is the leader in advanced silicon-anode lithium-ion battery development and production. The company's proprietary 3D cell architecture increases energy density and maintains high cycle life. Enovix is building an advanced silicon-anode lithium-ion battery production facility in the U.S. for volume production. The company's initial goal is to provide designers of category-leading mobile devices with a high-energy battery so they can create more innovative and effective portable products. Enovix is also developing its 3D cell technology and production process for the electric vehicle and energy storage markets to help enable widespread utilization of renewable energy. For more information, go to **www.enovix.com**

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