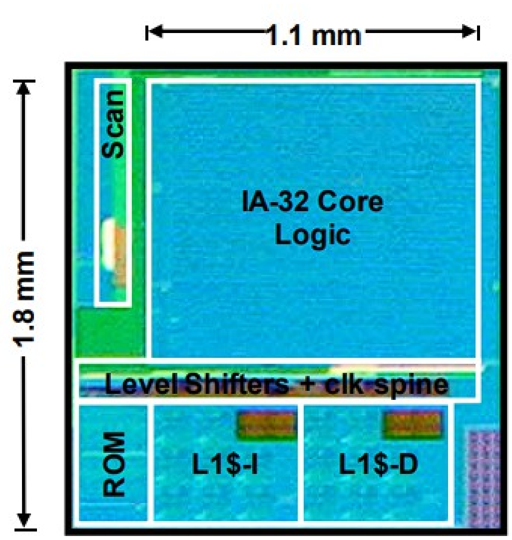
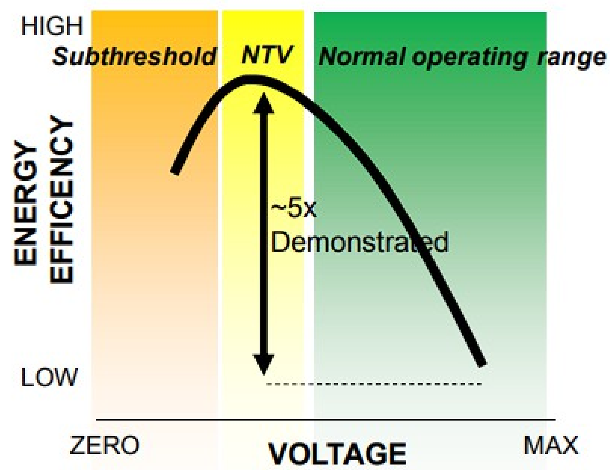
1. What you propose to do and how (<u>summary of at least 500 words</u>)

Energy autarkic hardware is an emerging design principle in devices such as IoT and wearables. General purpose processors with energy autarkic system design have yet to be commercialized. Energy autarky enables energy independence at the portable level, with solar panels on phones and laptops, but also other power sources. Energy autarky treats energy similar to zero-trust computer security, thus does not expect reliable access to energy grids. The design methodology of energy-autarkic hardware necessitates some of the most leading edge technologies, such as near-threshold voltage processors (sub 30nm nodes), ultra-low refresh (<10fps for low priority notification apps) low-power displays with non-emissive backlights, ultralow power nbIoT/LTE modems with advanced idle states such as eDRX, heterogeneous chiplets, Libre EDA tools, and low power microkernels. The integration of specific power limits for all hardware components ensures mobile devices can operate even at 100% CPU utilization, without a net decrease in lithium ion capacitance.

a.) To work with foundries to develop a near-threshold voltage cell library(ies) that can be used by



Pentium ®, 32 nm CMOS



Ultra-low Power	Energy Efficient	High Performance
280 mV	0.45 V	1.2 V
3 MHz	60 MHz	915 MHz
2 mW	10 mW	737 mW
1500 Mips/W	5830 Mips/W	1240 Mips/W

open cores, such as libre-SoC https://libre-soc.org/ . Efforts to develop sub-threshold voltage appear to be fraught with high risk, (Ambiq is an exception) while near threshold is more supported by foundries (Source: https://semiengineering.com/dealing-with-sub-threshold-variation/ , https://www.eetimes.com/arm-preps-near-threshold-processor-for-iot/# https://semiengineering.com/near-threshold-computing-2/ https://www.electronicdesign.com/technologies/analog/article/21807652/whats-all-this-subthreshold-stuff-anyhow https://www.mdpi.com/2079-9268/10/2/16 (^pic)
https://www.eejournal.com/article/0-6v-and-still-the-memory-persisted/

b). To integrate several low power components, by working with existing research groups in their respective areas of research (wireless, cpu/ISA design, kernel, memory, and display driver development), to develop a modular and interoperable chiplet:

The first expenditure is to hire a computer engineer to draft the open standard for a modular, "Chiplet-
based System In a Package." This would involve defining interposer framework for chiplets that connect solar panel power management systems, integrated circuits, lithium ion capacitors, as well as the instruction set architectures that can support either a heterogeneous carrier board, or monolithic versatile system on a chip for general purpose computing. Thus, the funding request is to identify a specialist who can identify the electrical requirements to develop a VLSI or glue-logic based ICs for solar-integrated system on a package.

While I have identified some of the lowest-power components commercially available over the course of two years, a specialist or specialists would be needed to identify electric wiring standards for energy
generation, storage, memory, and display, using a unified autarkic thermal power limit. Thus the TDP establishes the framework for the VLSI, while the engineer defines the ratio of each component's TDP to maintain a continuous operation. As capacitors are unable to provide a continuous discharge, lithium
ion capacitors appear to offer both continuous discharge, similar to a battery, as well as a long cycle life.
A tentative list of leading components:
1. Solar Power & Battery Management
https://www.tindie.com/products/jaspersikken/solar-harvesting-into-lithium-ion-capacitor/
https://www.powerfilmsolar.com/products/development-kits/solar-development-kit
2. Microcontroller & Memory
https://ambiq.com/apollo4/ 5uA/Mhz
3. Linux/RTOS software development--EKA2 https://en.wikipedia.org/wiki/EKA2 (uses just a single processor for both signal stack and OS, unlike prior processors before and after it, saving costs)
https://github.com/SymbianSource/oss.FCL.sf.os.kernelhwsrv/tree/master/kernel/eka
https://en.wikipedia.org/wiki/Zephyr_(operating_system)
QNX microkernel http://www.qnx.com/news/pr_2471_2.html
4. E-paper/Reflective Display driver
https://www.youtube.com/watch?v=BD4At2-e87E SHARP Memory in Pixel 4.4" RLCD LPM044M141A
between 250uW and 2mW:
https://os.mbed.com/media/uploads/JDI_Mbed_Team/lineup_from_draft_rev3_jdi_gr_mip_reflective_color_lcd_and_standard_products_20180219-3.pdf
5. Multi-band LTE Cat NB2 module https://www.quectel.com/product/lpwa-bc660k-gl-nb2

2. **Why it is beneficial to DOE:**
   Energy efficiency in FOSS (free and open source software) and hardware design allows for transformative technology developments and reduces future non-recoverable engineering costs (NRE) when reusing core IP libraries.

Current NSF funding grants, such as Intermittent Computing, use a different approach to energy efficiency-capacitors, and thus one incompatible with legacy software.

p.13 of Protean [paper](#):

“This research is based upon work supported by the National Science Foundation (NSF) under award numbers, CNS-2145584, CNS2038853, and CNS-2030251. It was also supported by the Netherlands Organisation for Scientific Research (NWO), and partly funded by the Dutch Ministry of Economic Affairs (EZK), through TTW Perspective program ZERO (P15-06) within Project P1. “

p.7 of Protean [paper](#):

"Carrier Board: The board was designed for ease of use and extensive flexibility for benchtop and real-world experimentation. Sparkfun’s MicroMod [82] M.2 connector is used to connect processor boards to the carrier. An array of eight tantalum capacitors (removable) provide energy storage, and a screw terminal allows energy storage expansion for radial capacitors"

"https://www.digikey.com/en/blog/lithium-ion-capacitors-can-help-you-provide-high-quality-power

"LICs provide a great third option when designing distributed power quality solutions for harsh environments. Their hybrid structures combine aspects of Li-ion batteries and EDLCs in a single device. They offer long cycle lives and high energy densities, and their **extended discharge over a few minutes instead of seconds can be an important distinction in power quality solutions on the edge.** LICs can produce smaller, more rugged, and safer solutions. Of course, good system design practices are needed to obtain their maximum benefit."'

By contrast, LICs appear to be a a lot simpler to drop-in for new SoC design than to use completely batteryless capacitors, with incompatible power management software. The minutes (or hours duration) allows more time to recharge a device, essentially allowing the top-off scheme to work in a way that does not cause sudden power intermittency issues that capacitors have, along with possible write errors that can occur during short power operations.

LICs in portable form factors have capacities from 80mA-400mA, rivaling some feature phones, thus the engineering effort for this project is centered on identifying and integrating ultra-low power consuming components, so that the device can operate continuously, rather than designing the platform around intermittent computing. LICS are in essence, a “hybrid” option, one underutilized, as the technology is relatively unknown, yet no less mature than other off-the-shelf technologies available.

The definition of technological convergence explicitly identifies “unrelated:”

“Technological convergence is the tendency for technologies that were originally unrelated to become more closely integrated and even unified as they develop and advance. For example, watches, telephones, television, computers, and social media platforms began as separate and mostly unrelated technologies, but have converged in many ways into an interrelated telecommunication, media, and technology industry. “

Thus, the motivation of this project is using the same inspiration that Apple used to develop the “Apple II” and the all in one “Lisa” computer in 1983. In the 2013 movie “Jobs,” Steve Jobs visits the Byte Shop store to deliver the 50 motherboards that the shop owner purchased for $500 each. The shop owner makes the claim that users want an appliance, since they do not know how to assemble the board. Jobs responded by adopting that idea in his second version.

“After a failed sale at his employer company HP, Wozniak reluctantly demonstrates the Apple I at the Homebrew Computer Club to a bored audience. Jobs is later approached by store owner Paul Terrell (Brad William Henke) who shows interest in the Apple I.
Terrell's disappointment in the Apple I (in his opinion, being only a motherboard and not a full computer as promised), inspires Jobs to restart with a second model. He hires Rod Holt (Ron Eldard) to re-conceptualize the power supply for what will be called the Apple II. Mike Markkula (Dermot Mulroney), a venture capitalist, notices Jobs and Wozniak's work, and also joins Apple. The Apple II is released at the 1977 West Coast Computer Faire where it is a remarkable success.
https://en.wikipedia.org/wiki/Jobs_(film)'

“The heat buildup using even my own power supply design (inefficient type) would have been too great. Steve [Jobs] tapped an Atari engineer, Rod Holt, to design a switching power supply that was much more efficient and generated less heat. Rod also keyed us into the fact that the plastic case wouldn't conduct heat well. At this point in time we took pride in being the first computer to use a switching power supply. “ https://en.wikipedia.org/wiki/Rod_Holt

The components that are unrelated or novel application in the above scene are the mainframe (PC) switching adapter (power supply). CRT, and keyboard (typewriter).

In this sense, there are a lot of intelligent developments and developers in fields such as AI, IoT, LICS, Near-threshold computing, but like Paul Terrell realized, many of these technologies do not have any immediate application or simple learning curve to average users. They certainly fit industrial applications such as monitoring sensors, but their application is much wider than that. Steve Jobs was one of the first entrepreneurs to understand the marketability of high-tech innovations by integrating their features into a new platform- the personal computer, and developed a user interface to allow it to be accessible to a wider audience.

The integration of unrelated technologies to develop appliance like products, similar to the smart-phone continues, but energy efficiency as a design feature has often been overlooked, preventing the development of autarkic phones and computers as appliances. The proverb “Two steps forward, one step back” has resonance here, but the sequence does too. By taking one step back, I am referring to a simplification of the definition of a mobile phone, pre-convergence of many modern features, such as satellite communication, GPS, camera phone. As the early cell phones had none of these features, they were primarily used for phone calls and texts. This remains the bread and butter feature of many phones today, albeit in new formats (group chat, Facetime, etc).

Koomey's Law shows that the power consumption of devices today for the same number of transistors decreases approx every 2.6 years. However the rate of decrease is less of an issue, as the manufacturing capabilities of leading edge foundries sub 30nm already allow for autarkic designs. Thus, concerns with the slowing of Moore's and Koomey's Law are moreso concerns with the ability to condense more features into existing products, rather than the de-convergence of often extraneous features and hardware components that some users may want to opt-out of. By carefully tailoring the components to a user's needs, mobile computers can be autarkic by supporting fewer applications, yet versatile with a heterogeneous hardware platform design, thus allowing the upgradeability of a device similar to computer motherboards that use the modular ATX standard (albeit in a smaller factor). There are many industries, such as Newegg, iBUYPOWER and NZXT, that source off-the-shelf components and build custom PCs for users who select the systems they want. This market can be imitated for mobile phone platforms, as lots of phone components outlive the operating systems' support (as Android and iOS typically lose support after 3-4 years). Thus, components such as solar panels, displays, lithium ion capacitors, can be re-used with newer processors- this is one of the goals of the EOMA68 project: https://www.crowdsupply.com/eoma68/micro-desktop One of the limitations of that project, however, is that it is not energy autarkic. Re-using the form factor, or adopting Leighton's other CPU, the Libre-SOC: https://libre-soc.org/, could allow the architecture to be tailored for an energy-autarkic device, one offering userspace appliations (linux desktop, feature phones). Thus, one of the major funding requests of this grant is to obtain funding for foundries (Intel/Skywater) willing to develop cell libraries for NTV, so that NTV CPU core architecture can be used in more general purpose platforms than ones such as used in microcontrollers, such as Ambiq Micro's Apollo series, and in devices such as the EOMA68 and phones/tablets. TSMC uses 22nm ULP and ULL Libraries for Ambiq Apollo4: https://ambiq.com/arm-enables-the-lowest-power-iot-devices-with-new-ambiq-apollo4-soc-on-tsmc-22nm-ulp-and-ull-libraries/

I recommend consulting with some of the most knowledgeable experts in LICS: https://nl.linkedin.com/in/jaspersikken https://github.com/hishizuka/pizero_bikecomputer https://www.j-display.com/english/ Developing a general purpose display driver for memory in pixel displays would appear to require some significant investments; however there do not appear to be many alternatives to low power screens or than e-ink, which use significant power per refresh. JPD screens can use more than 6.5fps: https://www.youtube.com/watch?v=S1MM8y0zOPw (up to 30fps) https://qiita.com/hishi/items/669ce474fcd76bdce1f1 However, as can be seen from the results, frequent refreshes result in higher power consumption. What this project aims to achieve is allowing the user to toggle the refresh rate, from 0.5s to 30fps or more, to provide more energy efficient options for using displays, so as to allow autarkic capabilities. Since MIPS displays are relatively expensive ($95 for 4.4, $54 for 2.7'), this project's grant request could also be seek to develop more research into cost-reduction of MIPS display manufacturing as well. The sharp quality of MIPS, in addition to the option to have no backlight, can also lead to improved eye health, as many smartphones have very bright backlights, even at their lowest settings.

3. **How the technology meets DOE's mission (www.doe.gov/about/index.htm).**

   Energy autarkic mobile system design helps ensure America's energy security by lessening the dependence on the energy grid for essential communication and computing needs, while reducing e-waste in the environment.

	Supercapacitor (EDLC)	Lithium Ion Capacitor (LIC)	Lithium Ion Battery (LIB)
Operating temperature	-40 to +85	-40 to +70	0 to 45 (charge) -20 to 60 (discharge)
Voltage	0 - 2.7V	2.5 - 3.8V	2.5 - 4.2V
Internal resistance	low	medium	high
Price	2 USD for 10F (need 2)	1.90 USD for 250F (compares to 90 mAh battery)	1.15 USD for 100 mAh
Max charge rate	1000 C	100 C	1 C
Charge time	<1 second	seconds	1 hour
Charge cycles	100k	100k	500-1000
Self-discharge per month	5-40%	5% or less	5% or less
Safety	safe	safe	Requires safety circuit, leakage, explosion, fire
Toxic	no	no	yes
Shipping and disposal restrictions	no	no	yes
Energy density Wh/kg	5-7	30 – 50	250
Power density (W/kg)	Up to 10,000	2000	1,000–3,000