Project Description

Intellectual Merit

The NSF rated as "Competitive" Proposal 2317155 "A Novel Current Sensor for Electricity Monitoring" but declined to support it. The Program Manager indicated that the NSF might consider a revised proposal if NSF concerns were addressed. Accordingly, this revised Proposal incorporates improvements to Proposal 2317155.

As before, the technical innovation is a novel sensor for a low-cost electricity monitor that rapidly displays a home's electricity use on a user's smartphone, and that anyone – even a child - can safely and easily install, without the services of an electrician. Electricity monitor use usually engenders behavior modification that reduces consumption by about 5% to 10%.

The goal of the project is to achieve proof-of-concept by developing, building, and testing a prototype monitor.

What is preventing the widespread adoption and use of residential electricity monitors, at a time when electricity bills are soaring? It is not unavailability; a variety of monitors have been available for decades. It is not lack of accuracy; only rough indications of consumption are needed to help consumers reduce their electricity bills, and many available monitors are far more accurate than is necessary. Rather, the dominant barriers to widespread adoption are the inconvenience, hazard, and high cost of installation of conventional monitors.

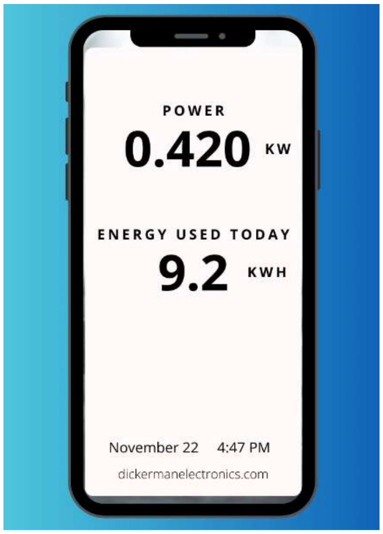
Most conventional whole-house monitors use multiple current sensors that must be mounted on individual conductors inside a home's circuit breaker (CB) panel, after first removing the front cover of the CB panel. Most conventional monitors must also be hard-wired to 120 VAC for power inside the CB panel. This exposes an installer to live uninsulated conductors and shock hazards. Consequently, safety and liability concerns dictate that conventional monitors should be installed by licensed electricians; this is stated explicitly in most conventional monitors' user manuals.

In contrast, the original proposal was for a novel sensor that clamped onto the cable from the utility meter, entirely outside the CB panel. However, as I considered revising the original proposal, it became clear that a technical pivot would be advantageous.

This pivot is to change the location of the sensor again. Rather than clamping the sensor on the meter cable, the user will slide the sensor over the utility meter, and mount it on the meter socket cover. In the photo at left, the red ring represents the novel electricity sensor at its new location. It comprises a pickup array and other electronics arranged on a 7" diameter ring that encircles the meter.

Thus, the proposed sensor is much easier and safer to install than a conventional monitor. It is mounted externally to all electrical panels, conduits, and enclosures. Here, all surfaces are either insulated or grounded, and no hazardous exposed conductors are present. This means that no live uninsulated conductors are exposed or encountered during installation. Therefore, the novel sensor can be safely installed by anyone, without the aid of an electrician.

Instructing a non-technical user in how to place a sensor on the meter socket cover will be much easier than for placing a sensor on a cable. Cable mounting requires that the user first identify the correct cable within a rat's nest of other cables entering the circuit breaker panel, sometimes at an awkward height.



Instead, the user can simply be instructed to "place the sensor on your utility meter", referring to a photo of an installed monitor (like the picture above). All meter socket openings look almost alike; if you walk or drive around your neighborhood and look at people's electricity meters, you will find the uniformity to be striking. Furthermore, utilities mandate that meters be exposed and accessible, and mounted at face height, for easy access.

Thus, the change in sensor location yields a breakthrough in ease of installation, which is essential for wide adoption. It also significantly increases the number of dwellings that the sensor is compatible with, because all utility meters are accessible, whereas some meter cables are hidden within walls.

A cell phone with a example display of power and energy is shown here.

A major concern expressed by the review panel was that the original novel current sensor might infringe on an Analog Devices (AD) patent. Since the devices of the revised proposal will not be solving systems of simultaneous non-linear equations, this patent infringement concern is eliminated.

Conventional current sensors use a direct application of Ampere's current law:

$$I = \oint \overline{H} * d\overline{L}$$

This states that the total current I within a closed path around a conductor, with differential length element $d\overline{L}$, is equal to the closed line integral of the dot product of the magnetic field $\overline{H}$ and the differential length element $d\overline{L}$. This holds regardless of the path chosen, as long as the path surrounds the conductor. Thus, conventional current sensors integrate the magnetic field H in a closed loop around a single conductor to determine the current I in the conductor.

Conventional current sensors essentially perform the Ampere's current law line integral. A typical conventional current sensor is a current transformer (CT) having an iron core that encircles a single conductor whose current is to be measured, or a Rogowski coil, which is a helical coil that encircles a single conductor whose current is to be measured.

Conventional sensors do have one advantage: they don't have to be precisely placed; they simply must encircle the single target conductor. However, conventional sensors cannot be used outside the meter socket enclosure to measure currents in a utility watt-hour meter, because the current-carrying conductors (HOT1, HOT2, and NEUTRAL) are not individually accessible – i.e., the conductors cannot be encircled one at a time. Furthermore, if the group of three conductors is encircled, the measured current will always be zero, if the installation is properly wired and has no ground faults.

In other words, conventional sensors must measure current in only one conductor at a time. Consequently, conventional monitors require removal of the front cover of the CB panel during installation. Inside the CB panel, the cable conductors are separated and stripped for separate connections to the HOT1 and HOT2 bus bars. Once the front cover is removed, a conventional current sensor can be used to encircle each of the two conductors separately.

In contrast, the novel sensor does not rely on Ampere's current law. Instead, the novel current sensor is based on the principle that the magnetic field $\overline{H}$ produced by a current I in a conductor at any point in space is determined by the Biot-Savart law. The differential form of this law is:

$$d\overline{H} = \frac{I d\overline{L} \times \overline{a_R}}{4\pi R^2}$$

This states that at a point in space connected to the location of differential conductor element $d\overline{L}$ by a vector with length R and with unit direction vector $\overline{a_R}$, the magnitude of differential field $d\overline{H}$ is equal to the product of I, $d\overline{L}$, and the sine of the angle θ between $d\overline{L}$ and $\overline{a_R}$, divided by R^2 and a constant 4π. The direction of $d\overline{H}$ is perpendicular to the plane containing $d\overline{L}$ and $\overline{a_R}$. If multiple conductor elements are present, their contributions combine by simple superposition in air.

The integral form of the Biot-Savart law implies integration along the path of a closed-loop conductor:

$$\overline{H} = \oint \frac{I d\overline{L} \times \overline{a_R}}{4\pi R^2}$$

The Biot-Savart law may be used to guide the design of a magnetic sensor. A basic visualization of the field lines produced by a current-carrying conductor element $d\overline{L}$ would be a cloud of circles centered on the current element, the circles lying on planes perpendicular to the axis of the current element, with the field lines looping around the current element in a direction determined by the right-hand rule. A 3-D plot of constant magnetic field strength would form a "donut-like" toroidal surface around the current element, because the field strength decreases as the angle between vectors $d\overline{L}$ and $\overline{a_R}$ decreases, and as R^2 gets larger. Therefore, the output of a magnetic pickup using this principle will vary with its distance R from, and angle θ to, the target conductor element (as well as the orientation of its axis to the field line).

Accordingly, an important and novel aspect of the proposed sensor is that it exploits the standardization of residential utility meters and sockets (see, e.g., Figures 1 and 2 below). This standardization results in a uniformity of conductor geometry that is unmatched in any other part of the residential service entrance equipment. This uniformity can be used to predetermine the relative orientation and spacing of a sensor with respect to a target current-carrying conductor, thereby eliminating variations in R and θ.

Fig. 1

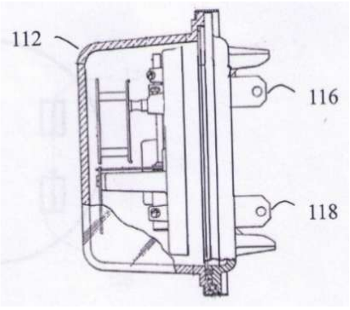


Fig. 2

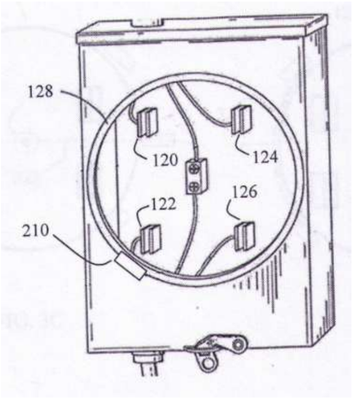


Fig. 1 shows a side view of a typical utility watthour meter 112 with current-carrying connector blades 116, 118. Fig. 2 shows a typical meter socket that the meter 112 would plug into.

Essentially all residential meter equipments are ANSI Form 2S, similar to those shown in Figures 1 and 2, which means that the meter 112 has four connector blades, dubbed “stabs”. In the side view of Fig. 1, two of the four stabs, shown as 116, 118, can be seen. The locations and dimensions of the stabs are fixed and known. When the meter is plugged into the meter socket, the male stabs mate with corresponding female terminals, dubbed ”jaws” (shown in Fig. 2 as 120, 122, 124, 126) that are located within the meter socket. A first line current I_{L1} flows from jaw 120 through the meter to jaw 122, and a second line current I_{L2} flows from jaw 124 through the meter to jaw 126. Power always flows from the top two jaws to the bottom two jaws.

The novel current sensor’s magnetic sensors, or “pickups”, target magnetic fields caused by the current flowing in the various four jaw-stab pairs. In Fig. 2, pickup 210 targets jaw 122. Because the positions of the stabs and jaws are fixed and known, R and θ are made constant. Because the direction of power flow is known, and because the spacings between the four jaw-stab pairs are relatively large, the magnetic field measurements may be converted to current estimates as simply as by multiplying by suitable gain constants (although more sophisticated processing may be employed). Thus, the Biot-Savart law may be relied upon, and the use of non-linear equation solvers is eliminated.

Although all residential meter sockets look very similar, they do come in two slightly different styles: ring-style and ringless. Ring-style sockets use a lockable ring clamp to prevent or detect unauthorized removal of the meter. Ringless sockets use a lockable panel for the same purpose. These two styles must ultimately be accounted for in the design of the mounting method for a finished electricity monitor product.

In addition to the ease of installation, safety, and compatibility advantages mentioned above, sensing at the meter socket provides several other important technical advantages:

1. The neutral conductor does not enter the meter itself. This provides some isolation of any neutral current $I_{Neutral}$ from the two line currents I_{L1} and I_{L2}, making the two targeted line currents easier to measure. This also eliminates the task of identifying the neutral conductor.
2. The accuracy requirements for magnetic field measurements may be considerably relaxed because (possibly sensitive) equation solvers and their convergence challenges are eliminated.
3. The pickup signals may be combined into as little as one or two groups before being processed by synchronous detection, so fewer analyzer channels are required. This yields less hardware, lower cost, and longer battery life.
4. Because the novel sensor is typically installed outdoors, solar power is a possibility, and this could ultimately eliminate battery replacement.

Fig. 3 shows an example of a novel current sensor assembly that would slide over a utility meter, encircling it. The monitor sensor hardware comprises a mounting base 814 with four magnetic pickup coils, indicated by the four rectangles 210, 310, 312, 314. The base 814, or a nearby printed circuit board (PCB), also holds analog and digital signal conditioning circuitry, and a Bluetooth Low Energy (BLE) radio and processor; these aren’t shown in Fig. 3.

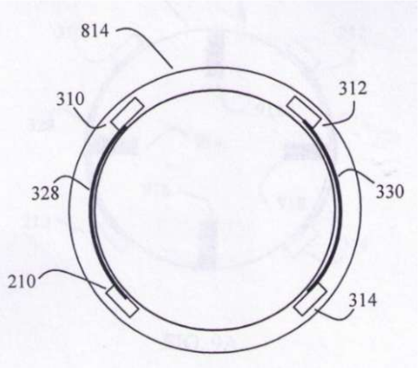


Fig. 3

In one example, the outputs of the left pair of pickups 210, 310 are combined, and the outputs of the right pair of pickups 312,314 are combined. The two group signals are processed by a two-channel, dual-phase synchronous detector using an a.c. line-voltage reference signal, and lowpass filtered (LPF). The synchronous detector outputs are measured and recorded separately by a data acquisition subsystem on the sensor assembly. In another example, all four of the pickup signals are combined and connected to a single-channel, dual-phase synchronous detector.

The data is transmitted from the sensor assembly to a cell phone using the Bluetooth radio. The cell phone runs an app that processes sensor data to calculate electricity use and displays power and energy usage.

The a.c. line-voltage reference signal for the synchronous detector can be provided by a capacitively-coupled voltage phase sensor using electrodes 328, 330, which couple to the two line-current conductors L1 and L2 by parasitic capacitance through the meter dome to sense the phase of the power line voltage. Because powerline frequency is so tightly controlled (typically 60.00 Hz +/- 0.06 Hz), the output of the voltage phase sensor can be used as the reference input to a Phase-Locked Loop (PLL) having a very narrow operating frequency range, and being driven by a 32.768 KHz watch crystal oscillator. This arrangement can provide rejection of reactive power (drawn by non-unity power factor motor loads) if a phase lock is maintained. However, when a dual-phase synchronous detector is used, even if phase lock is lost, the detector can still operate as a “nearly synchronous detector”, thereby allowing a very low bandwidth LPF with good sensitivity and noise rejection, albeit without rejection of reactive power. If phase lock is lost, the detector may be susceptible to capacitive coupling of the line voltage signal, so the magnetic pickups (which are intended to respond only to current) may need electrostatic shielding to mitigate any response to line voltage.

The current sensor may be powered by one or two AAA alkaline or lithium ion batteries, and be protected by a plastic housing, for example. Solar power may be considered in Phase II.

The drawing of Fig. 3 shows a flat mounting base, which could be part of a rigid circular insulating housing with an annular ring shape; the pickups shown here might be connected to a nearby small rigid PCB. Alternatively, the base might itself comprise a rigid PCB. Another alternative is to use a flex circuit (flexible circuit) that is essentially wrapped in a band around the base of the watthour meter, all enclosed by a rigid circular insulating housing that registers the pickup positions with respect to the meter cover opening. This would reduce PCB panel waste and cost during fabrication, compared to a rigid annular ring PCB. It might also be more universally applicable to ring-style and ringless sockets, because it allows a very low profile near the base of the meter dome, thereby avoiding possible mechanical interference with a ring-style socket’s ring lock. Another alternative with the same low profile is a small rigid PCB connected to a flex circuit on each side to connect to pickups, again inside a rigid circular insulating housing.

As mentioned above, an important technical innovation is the identification of the utility watthour meter and socket as optimal sites for a magnetic pickup array. If a magnetic pickup having a predetermined sensitivity is placed at a predetermined distance from, and at a predetermined orientation to, a current-carrying conductor segment located in the meter assembly, then the magnetic field “seen” by the pickup will be substantially predetermined by the Biot-Savart law, as described above. The development of the final magnetic pickup configuration will be another aspect of this technical innovation. Another innovation is the placement of electrodes (328, 330 in Fig. 3 above) near the utility meter, for use with a capacitive voltage phase sensor, to sense the phase of the ambient electric field associated with the voltage on meter. The output of the voltage phase detector can then be used as a reference signal for synchronous detectors used in the current sensor. A synchronous detector can increase sensitivity and, as mentioned above, if provided with a reference signal having a known phase with respect to the line voltage, can mitigate power factor (PF) error by detecting a component of the current that is in phase with the line voltage. Yet another innovation is the use of a dual-phase “nearly synchronous detector”, mentioned above, that can increase sensitivity even in the event that the phase of the voltage cannot be detected – for example, in the case wherein a utility meter dome has an electrostatic shield.

The pictures of Figures 4-6 show some of the work done to establish initial magnetic pickup placements. Figures 4 and 5 are Vizimag simulator field plots for long conductors (these are simplified models for the mated jaws and stabs). Fig. 4 is a field pattern for current in just L1, and Fig. 5 is a pattern for currents in both L1 and L2. Fig. 6 is a view of a lab test bench on which low voltage (< 10VAC) tests of current sensors were done. The instrument on the upper left is the lock-in amplifier used to measure pickup signals. The two red curved objects on bottom left are PCBs that I designed and had fabricated to help test pickup configurations. The red ring on the meter socket is an array of four of these PCBs with inductors used as magnetic field pickups.

Fig. 4

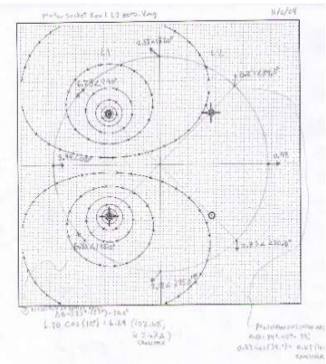


Fig. 5

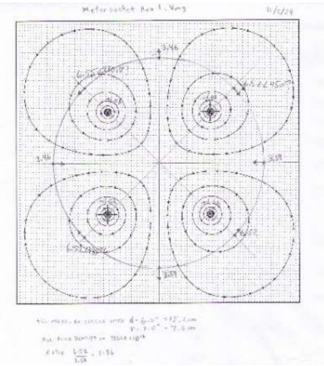


Fig. 6

Initial lab test results were encouraging. Using the lock-in amplifier with a hard-wired line voltage reference input, and a 6-pickup configuration on a ringless socket with overhead feed, and a collection of 9 different utility meters from 7 different manufacturers, I measured an average gain of 64.9 uV/A, with a tolerance of +16.0% / -12.0%. This uncalibrated gain tolerance is easily small enough to be satisfactory for the purpose of helping consumers to reduce their electricity bills.

Next, I tested with different varieties of field wiring, including two versions of underground feed, as well as for overhead feed. The results showed that a 4-pickup configuration yields about a +/- 5.0 % gain tolerance over the variety of field wirings, versus a larger approximately +/- 15.0 % for the 6-pickup configuration, for any given watthour meter. For this reason I am inclined to use a 4-pickup configuration for the project going forward.

Then I evaluated the effect of ring style mounting versus ringless on gain tolerance, by testing five non-electromechanical watthour meters in a ring style meter socket, and found that, all other things being equal, the ring style mounting changed the 4-pickup gain (vs. that for ringless mounting) by amounts ranging from -2.0% to +12.0 %. It seems likely that, by adjusting the relative spacing to the meter socket cover or meter ring, this tolerance can be centered, i.e., made to be +/- 7.0%. Determining an appropriate relative spacing will be part of the project.

Gain variations due to variations in registration (position errors) of the magnetic pickups with respect to the targeted conductors were almost negligible with the 4-pickup configuration. Shifting the pickup array off-center by +/- 0.2” caused < 1.0% change in the novel sensor readings in bench tests of ring style mounting.

I also measured my own home’s whole-house power using the 4-pickup novel current sensor concept and compared the resulting measurements to those made simultaneously using a conventional TED whole-house electricity monitor. Fig. 7 shows the 4-pickup current sensor installed outdoors on the live utility watthour meter outside my home. Fig. 8 shows a close-up view of the deployed sensor. Again, the red ring encircling the utility watthour meter is an array of four PCBs, having a total of four inductors used as magnetic field pickups (as in Fig. 3). The array was connected to the lock-in amplifier in the basement with a 20’ coaxial cable (the black cable with drip loop in Figures 7 and 8) by passing the cable through a basement window. Fig. 9 again shows the lock-in amplifier, and, stacked on top, a KILL A WATT monitor (grey box on left) for monitoring line voltage, and the TED whole-house electricity monitor display (blue and white box on top right) for measuring power. The utility watthour meter at my home is an electromechanical rotating disk Schlumberger. Previously, I had purchased the same model of Schlumberger and characterized it on the bench. When I used the gain that I had previously measured on the bench for the Schlumberger (43.4 uV/A), and subtracted an offset of 66.0 uV (more on this below), all of the novel sensor power readings, numbering about a dozen and ranging from about 170.0 W to 6000.0 W, matched the conventional TED monitor readings within +/- 1.0 % to +/- 7.0 %.

Fig. 7

Fig. 8

Fig. 9

A wider selection of meters and different meter socket field wiring configurations will cause somewhat greater variations in sensor gain. The final uncalibrated gain tolerance will determine the size of error in utility electric meter readings that can be reliably detected without any calibration of the monitor, and so there is some risk that certain users won’t be satisfied with the sensor accuracy.

Therefore, one goal of the project will be to develop, test, and finalize a pickup coil configuration that minimizes gain tolerance. Configuration choices include the number of pickups, locations of pickups, orientation of pickups, phasing of pickups, and sensitivity and core material of each pickup. Final testing will be done with lab mock-ups of both overhead and underground feed wiring, and both ring-style and ringless meter sockets, with at least 9 different utility meters from 7 different manufacturers.

The accuracy risk will be mitigated by several factors:

1. Most users just want to reduce their electricity bills. For that purpose, they only need rapid power readings that are approximately proportional to actual consumption. The actual “units” of the

numerical readings are less important than proportionality, because, to reduce consumption, a user will normally focus simply on reducing the displayed power and daily energy use numbers – whatever their "units". For this reason, an uncalibrated gain tolerance of even +/- 50.0 % or more would likely be usable for most consumers.

2. Model-to-model internal watthour meter conductor geometry differences account for most of the possible gain tolerance. The app, as shipped, will be loaded with a default (generic) gain constant (52.0 uV/A), which could produce an approximate +/- 30.0 % gain error in the worst case. To mitigate this gain error, the app will allow the user to select their model of utility watthour meter from a pop-up list (much like selecting a printer driver for a computer). The app will then use a pre-determined gain appropriate for that model of utility meter. As noted above, in the first whole-house tests at my home, this step reduced gain error to < 7.0 %.
3. In the whole-house testing with my home's legacy (rotating disk) Schlumberger utility watthour meter connected to 240 VAC, the 4-pickup sensor initially produced a fairly large AC offset error. An electrostatic shield (the copper ring visible in Fig. 8, connected to the meter socket chassis with the black grounding clip) between the meter internals and the pickup coils reduced the offset, but a 66.0 uV AC offset remained. This offset was too large to ignore, as it corresponded to a "power offset" of 365.0 W. My working hypothesis is that the 66.0 uV AC offset is caused by magnetic fields from a voltage sensing coil that is always "on" in the Schlumberger meter, as well as, perhaps, some residual capacitive coupling of AC voltage from L1, L2 that the shield couldn't completely eliminate. To solve this, the 66.0 uV AC offset error was nulled by subtracting 66.0 uV from all readings before converting them to Amperes. In the novel sensor's app, this issue can be dealt with by providing a "zero" function (like a "tare" function on a scale) to eliminate offset. The app "zero" function will instruct a user to "zero" the novel monitor by first shutting off all loads in the home (most easily done by temporarily flipping the main circuit breaker off) and then pressing a soft "zero" button in the app. Although the legacy Schlumberger watthour deployed at my home is scheduled to be retired by our local utility this summer, and any newer, non-rotating-disk meters will likely not produce this offset, the "zero" app feature may be needed for a few years, until all legacy rotating disk watthour meters have been decommissioned.
4. Users who desire even greater absolute accuracy can calibrate the whole house monitor by taking readings with an accurate plug-in power meter like a KILL A WATT® (these cost $10 to $20 and have accuracies of about +/- 1.0 % or better), and entering those readings and the corresponding novel whole house monitor readings into the app. The app can then adjust a gain constant to match the whole house readings to the plug-in meter readings. Newer watthour meters, vs. legacy rotating disk meters, tend to have better gain balance for currents in L1 versus L2. Therefore, as legacy rotating disk watthour meters are retired, this tactic should yield more and more accuracy.
5. Like some conventional monitors, the novel sensor, used by itself, doesn't directly measure line voltage. If the sensor is used without voltage calibration, variations in voltage can add up to +/- 10.0 % error in power readings. To further increase accuracy, users can manually enter a value for line voltage (read by user from KILL A WATT style appliance power meter, for example) to eliminate errors that might otherwise be caused by voltage variations from the nominal 120.0 VAC. Furthermore, it may eventually be possible for the novel monitor app to automatically acquire voltage measurements from an 3rd party plug-in monitor like the KILL A WATT®.
6. Finally, some customers will choose to calibrate the novel monitor by simply entering into the app the monthly energy usage shown on their electric utility bill, and then instructing the app to match the monitor's usage reading to the electric bill usage. Although this last tactic won't help to provide a better independent test of the accuracy of one's utility watthour meter, the novel monitor will still provide the advantages of convenient and rapid indications of power, which are the key requirements for using the monitor to reduce one's electricity bills.

Other risk elements are that radio range or battery life (if adequate solar power isn't provided) will be unsatisfactory to consumers. The project can address these risks by estimating performance, and by surveying prospective customer preferences for these features.

R&D Plan

I propose an 18-month project, with the principal investigator committing to working a minimum of 4 hours per day on the project.

In the original proposal, we planned to primarily use computer simulations to verify pickup configurations. For the revised proposal, initial simulations were done with a primitive ViziMag 2-d model. However, it would be difficult to model the large variety of routings of conductors, including field wiring, that are connected to the meter blades and socket jaws in the many different meters and meter sockets. Therefore, although some simulations may still be used, most of the verification work will be performed experimentally in a laboratory setting. This is reflected in the following milestones.

Milestones

1. Develop and finalize magnetic field sensor pickup configuration, including number of pickups, locations of pickups, orientation of pickups, phasing of pickups, and sensitivity and core material of each pickup. Characterize gain variation range in lab test fixture with commercial lock-in amplifier, first using a line-powered low-voltage transformer to provide the lock-in amplifier's reference signal. Test with ringless style and ring style meter sockets, "underground" and "overhead" feed wiring, and 9 different watt-hour meters of different make and model. Test with at least one watthour meter connected to 240 VAC, and with currents of at least 10.0 A. The goal is to limit uncalibrated gain error to approximately +/-50.0% or less for a default gain value, and without any user calibration (except a "zeroing" step, in some cases).
2. Develop a non-contact 240 VAC voltage phase sensor that detects the phase of the electric field surrounding utility meters. An acceptable phase error would be < +/- 10.0°, corresponding to a gain error of about +/- 1.5 %.
3. Develop an all-digital narrow-band phase-lock loop for 60.0 Hz +/- 0.06 Hz operation.
4. Purchase a dual-phase lock-in amplifier. Use it to verify "PLL out-of-lock" mode performance.
5. Develop a working "breadboard" of a complete front-end for the novel current sensor. The breadboard will include current pickup signal conditioning with a two-channel dual-phase synchronous detector, a 240 VAC voltage phase sensor, and an all-digital narrow-band phase-lock loop.
   - 5.1.1. Test the front-end breadboard on the bench to verify operation and performance, as in Milestone 1.
   - 5.1.2. Test the front-end breadboard by mounting it outdoors on a utility watthour meter that is in use at a residence, and compare measurements from the novel sensor to measurements from a conventional electricity monitor.
6. Develop a conceptual design for mechanical mounting, including mounting alignment element design, that is compatible with both ring-style and ringless meter sockets. Review and refine mechanical design concept with FinishLine mechanical engineering.
7. Develop a working "breadboard" for a BLE wireless connectivity subsystem, using an evaluation board, and test for range and power consumption.
8. Develop a complete electricity monitor prototype that can be mounted outdoors on a utility watthour meter for testing, including a custom PCB with current sensor front-end and a BLE wireless connectivity subsystem, and a primitive app for cell phone display of power. To

demonstrate a Minimum Viable Product (MVP), power the monitor with one or two lithium AAA batteries (solar power may be considered in Phase II). The prototype will be used to test performance and cost; important parameters and their assumed approximate acceptable values are: linearity error (< +/-5.0 % of Full Scale), uncalibrated gain error (< +/- 50.0 %), battery life (> 1 year), radio range (far enough to work in most single-family homes), parts count and cost (low enough to sell for < $40 to $80 each).

   8.1. Develop and review a concept for system design and electronic circuit design.
   8.2. Do prototype electronic PCB schematic and layout (rigid and/or semi-rigid and/or flex).
   8.3. Review electronic circuit design.
   8.4. Do preliminary mechanical design of enclosure, and fabricate enclosure.
   8.5. Order parts, order fabrication and SMT assembly of prototype PCB (rigid and/or flex).
   8.6. Write embedded software for prototype PCB microcontroller.
   8.7. Do prototype app development for cell phone. The app should have a BLE pairing interface, and a primitive user interface displaying power (“KW”) and energy(“KWh today”).
   8.8. Test and debug monitor protype on bench, as in Milestone 1, re-spin PCB if needed, debug and refine software.

9. Mount monitor prototype outdoors at residence, compare readings to conventional power monitor readings.
10. Estimate hardware per-unit cost with a preliminary bill of materials (BOM)
11. Prosecute patent application and file patent continuation or continuation-in-part, as appropriate.
12. Write final report.

Timeline

Q1 Begin project; develop magnetic pickup configuration, lab test; develop 240 VAC voltage phase sensor and PLL; lab test (Milestones 1-4)

Q2 Develop working breadboard for front end and wireless, test at residence, develop mechanical mounting concept (Milestone 5-7)

Q3 Start PCB schematic and layout (Milestones 8.1-8.3)

Q4, Finish PCB schematic and layout, PCB prototype fab, do enclosure design and fab, write embedded software for prototype PCB microcontroller and write app for cell phone (Milestones 8.1-8.7)

Q5 Test and debug monitor protype on bench, re-spin PCB if needed, debug software (Milestone 8.6-8.8)

Q6 mount monitor prototype outdoors at residence and test, compare readings to conventional power monitor readings, finish project (Milestones 9-12)

If the breadboard and prototype testing show that the performance limits detailed in Milestone 8, above, can be met, then technical feasibility and proof-of-concept will have been achieved.

In Phase II, the durability challenges associated with outdoor operation will be addressed, and the product design and app design can be refined and finalized. Field tests can be conducted with multiple prototype units, in which customers log energy readings and compare them to energy usage reported on their monthly utility bill to gauge accuracy, as well as to gauge ease of installation and use. Solar power can be designed in, if it is deemed desirable.

Company/Team

Dickerman Electronics is the company name that I, Bob Dickerman, used for my sole proprietorship consulting business, which was active until 2012. Most of my consulting service work was electronic circuit design and printed circuit board design for instrumentation, as well as in developing applications in signal processing. A resume can be found at my website[1].

Since 2012 I have been focused on developing proprietary, patented designs. I have collaborated with many outside experts, including engineering consultants and patent lawyers. A list of patents can be found at my website, including a patent application that specifically pertains to this proposal.

My interest in electricity monitors is not casual. I have spent considerable time over the past two decades surveying, studying, and using commercially-available residential electricity monitors. I have also designed and prototyped several different proprietary and novel electricity monitors, including a whole-house monitor, a 240 VAC appliance monitor, and some cable monitors. None were offered for sale, due to various shortcomings that made them too difficult to use for the average consumer. Below are photographs of some of the prototype monitors:

I believe that my prior work in this area constitutes good preparation for the technical challenges of this proposal.

I registered Dickerman Electronics in Northfield, MA as a sole proprietorship in 2014, although I had been filing business tax return Schedule C's as a sole proprietorship under the same DBA for two decades prior. For the past three years, I have been investing my own time and money to develop proprietary devices and file for patent protection. In those three years I had no sales or profits until 2022 when I was awarded $2000.00 for winning a Unified Patents PATROLL contest – ironically, to find prior art that will invalidate another company's patent (dubbed Guzik '220). I have had no prior government or outside private funding. I expect the company to continue as a sole proprietorship for at least the next two years or so while I spend most of my time on the electricity monitor project; I also need to spend some time attempting to monetize my existing patents.

To assist in product development, I budgeted money for a consultant. Finish Line PDS[2] of Hudson, NH, is a consulting company that supports startup companies with a broad range of product development services. Finish Line will consult on the prototype electronic circuit design and initial mechanical design of a prototype enclosure. Finish Line may also help with coding of embedded software running on the sensor board, and coding a simple smartphone app for the prototype, and with other product development tasks. Finish Line could also provide an independent Market Validation study and an independent Go to Market study, as discussed further below in "Commercialization Potential".

My equipment resources include a Stanford Research Systems SR510 Lock-In Amplifier for lab testing magnetic current sensor configurations that have very low sensitivity. To simulate targets for current sensor testing, I have acquired nine different used watt-hour meters from seven different manufacturers, and three watt-hour meter sockets, including both ringless and ring style sockets. I also have a collection of isolation transformers, Variac adjustable autotransformers, and heater loads that can be used to establish AC currents in the watt-hour meters and sockets during bench testing.

I have a working copy of Vizimag, a magnetic field analysis program that generates field plots from user-specified arrays of current-carrying conductors. I have used this for preliminary simulations.

Broader Impacts

The motivation for taking on this project is to benefit society and the natural world.

An electricity monitor based on the novel current sensor could have significant broader impacts if it were widely adopted, because it would produce significant economic and societal benefits to the United States. It could be widely adopted if it worked well, was available at a modest price, could be easily deployed by ordinary consumers without an electrician's services, and was skillfully and aggressively marketed.

The customer will typically be a U.S. homeowner or renter who wants to minimize their energy consumption and reduce their electricity bills.

For a single consumer that initially used 600.0 KWh/month, if monitor use prompted savings of 10%, over a 10-year monitor life the savings would be 7000.0 KWh. This is equivalent to saving 5,000 lbs. of coal and eliminating 10,000 lbs. of combustion byproducts, all by the use of a single monitor weighing perhaps 4.0 oz. At $0.20/KWh, this would save each consumer $1,400.00 in electricity costs over 10 years.

Such savings would have the biggest positive impact on the country's least-affluent citizens. The savings would be the greatest for those who live in places with the highest electricity prices, such as the Northeastern states and California, for example.

As discussed below in the "Commercialization Potential" section, market share for the novel monitor could be a significant fraction of 15.0 million units.

If 15.0 million units were deployed, over a 10-year period, this would be equivalent to saving 62.0 trillion cubic feet of natural gas, eliminating 140.0 billion lbs. of combustion byproducts, and saving $20 billion in United States consumers' electricity bills. At a $39.00/unit price, 15.0 million units would correspond to $600 million for the total addressable market, which would be a significant contribution to United States business activity and employment.

In addition, if it were widely adopted, the novel monitor would produce significant societal health and welfare benefits, because it would reduce the exposure of the populace to combustion byproducts.

Finally, the energy savings that would likely result from a broad deployment would help to bolster United States energy independence.

No unintended consequences of the proposed technology are expected.

Commercialization Potential

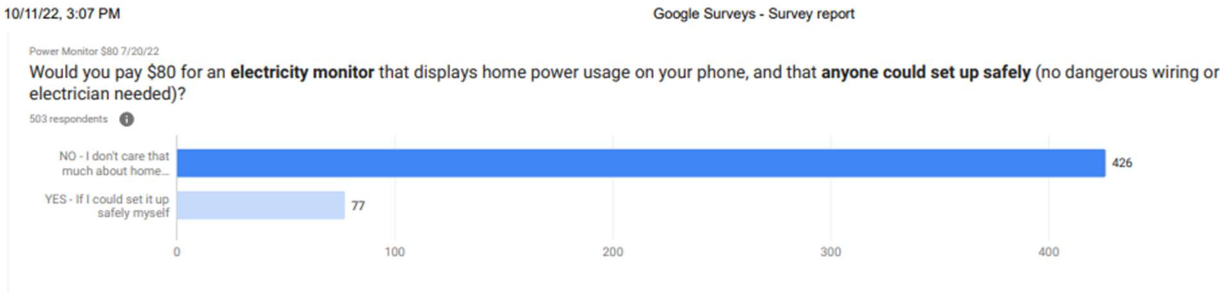
The review panel expressed concerns about market demand, writing that "the power industry has moved beyond behavior-based consumption reduction [to] central control." That may be true. However, central control isn't available in many places - and where it is available, consumers must purchase expensive, new, controllable appliances to gain any benefit from it. These new appliances can either automatically be controlled by utility systems, or can schedule operation to avoid Time Of Use (TOU) billing penalties. Many less-affluent consumers already struggle to pay their electricity bills, and they can't afford to purchase expensive new appliances. The proposed monitor will help these consumers to immediately reduce their bills and avoid TOU billing penalties - without making large cash outlays for new appliances.

The target market for the novel monitor is larger than that for conventional monitors. We will not only be targeting affluent home automation enthusiasts and tech “geeks” who would purchase conventional monitors - we will also be targeting the millions of less-affluent, less-technically-adept people who just want to reduce their electricity bills, who aren’t comfortable sticking their hands inside a live CB panel and doing electrical wiring, and who can’t afford to pay for an electrician to install a conventional monitor. Again, those who live in places with the highest electricity prices will be most motivated to use the novel monitor.

There are roughly 100 million households in the United States. To quantify interest, we conducted a Google Survey, with 502 U.S. respondents, as follows:

“Would you pay $80 for an **electricity monitor** that displays home power usage on your phone, and that **anyone could set up safely** (no dangerous wiring or electrician needed)?
YES – If I could set it up safely myself
NO – I don’t care that much about home power”

77 Respondents out of 502 in the survey (15.0%) answered “YES”, as shown in the screenshot below:



10/11/22, 3:07 PM

Google Surveys - Survey report

Power Monitor $80 7/20/22

Would you pay $80 for an **electricity monitor** that displays home power usage on your phone, and that **anyone could set up safely** (no dangerous wiring or electrician needed)?

503 respondents

Based on this survey, the total addressable market in the United States could be approximately:

100 million households x 0.15 are interested = 15 million units

At even a $39.00/unit price, this corresponds to $600 million for the addressable market. Market share could be a significant fraction of that, because the competition only sells monitors that are more dangerous, more costly, and much less convenient to install.

The value proposition for the novel monitor is as follows. The total cost is $39.00, and anyone can install it in a few minutes - without removing a CB panel cover. There is no liability because there is no electrical shock risk or fire hazard risk. For a single consumer that pays $0.20/KWh and who initially used 600.0 KWh/month, if monitor use prompted savings of 10%, the payback time for the novel monitor would be about 3 months. Over a 10-year monitor life the total savings in electricity costs would be about $1,400.00 – and the savings will be even greater if electricity prices rise.

In comparison, the value proposition for conventional monitors is much less attractive. If an electrician is paid $300 to install the conventional monitor, as is prudent for insurance and liability reasons, and as is recommended by manufacturers, then the total initial investment for such a conventional monitor is about $360 to $700, plus hours of the homeowner’s time. The payback time for such a conventional monitor is 3 to 5 years. This is 12 to 20 times longer than for the proposed novel monitor.

Purchase prices of conventional monitors range from about $60 to about $400, depending on features and options. The cheapest are called In Home Displays (IHDs), provided by some electric utilities in some areas. IHDs simply regurgitate, on an indoor display, the data generated by certain smart meters. IHDs are not widely available, they do not make independent measurements of electricity use, and many models update their readings slowly. Conversely, most conventional monitors that do make independent measurements of electricity use two conventional current transformers (CTs) that must be installed inside a CB panel, after removing the front cover of the CB panel[3]. And, again, the product literature for all conventional monitors typically recommends that consumers pay to have installation be done by a licensed electrician, for safety and liability reasons.

Nonetheless, investment and revenue figures for manufacturers of conventional monitors do provide ample evidence of interest in electricity monitoring for homes. For example, Sense raised $105.0 million in new venture capital investment for whole-house electricity monitor development in April 2022[4], and their 2024 revenue was about $12.0 million. Emporia's 2024 revenue was about $14.0 million (part of their revenue was from sales of smart EV chargers)[5]. Eyedro's 2024 revenue was about $40 million (part of their revenue was from sales of industrial and business monitors).

There is a previously established record of market demand for a "safe electricity monitor mounted at the utility meter". From 2004 to 2012, Blue Line Innovations and Black & Decker manufactured a battery-operated monitor that attached to a utility meter's glass dome, as shown in the images below.

By 2010, over 130,000 of these had been sold as a "safe … do-it-yourself (no electrician needed) solution for homeowners" for $137.99 each (considering inflation, that would be $182.13 each today). Note that these sales occurred despite widespread reports that the sensor was difficult to position correctly during installation. In fact, 10 pages of its user manual were dedicated just to sensor installation instructions. It had compatibility, quality, and reliability problems. It didn't even make an independent measurement of electricity usage. Instead, it just "looked at" the speed of the rotating wheel or the rate of a flashing LED on the utility meter's face. Consequently, it couldn't be used to make an independent test of a utility meter that a customer suspected of giving erroneously high readings. I purchased one of these, a Black & Decker monitor, for my own home in 2010, only to discover that it was incompatible with my utility meter and wouldn't work.

To directly address the question "Will People Buy This Product?", I ran a 2-hour market experiment with a Google display ad. The ad had a picture of a phone (like the one on page 2, above) having an energy display app, and text that said "Reduce Your Electricity Bills! An easy-to-use whole-house electricity monitor that anyone can install in 5 minutes!". There were 23,553 ad impressions. 175 people clicked on the ad, yielding a click-through rate (CTR) of about 0.75% (note that when the Google display ad was shown 10 times on pages with a topic related to the outdoors, it yielded a much higher CTR of 10.0%). Of the 175 people who clicked on the ad, about 80 people waited long enough for my slow website server to load my landing page[6] that described a mockup of the monitor. Those 80 people spent an average of about 3 minutes reading the page, and 2 of them ultimately clicked the "Order Now for $39" button. Obviously, this is a tiny sample, and the Google ad costs per order for this ad bid strategy were too high to be practical for an item that sells for $39, but, based on this result, we would obtain about 1 order per hour, or about 8,700 orders per year, based just on a prototype online display ad.

Some key advantages of the novel whole-house electricity monitor vs. the competition are:

1. The monitor is located outside of all electrical cabinets, so live, uninsulated conductors aren't encountered during installation. Therefore, anyone can safely install the monitor, without the aid of an electrician. This makes installation convenient, safe, and cheap.
2. There are no wires or cables to route and connect, and given its outdoor location, solar power might ultimately be used to even eliminate battery replacement.
3. Because the monitor's radio antenna is outside of all metal cabinets, radio design is eased. No external feedline or external antenna, and no penetrations of electrical enclosures, are needed.
4. The novel current sensor can use air-core magnetic pickup coils, which are smaller and lighter than iron-core current transformers. The novel monitor would likely be the lightest and smallest whole-house electricity monitor in the world. This would ultimately minimize e-waste.
5. Unlike the Black & Decker and Blueline sensor, the proposed sensor will likely mount on the customer's meter socket cover or meter ring, rather than on the utility meter itself. It will have minimal or no physical contact with the utility meter's dome. The sensor's low physical profile (lying close to the meter socket cover) won't hinder smart meter service or radio communication.
6. Unlike IHDs that just regurgitate utility meter measurements, the proposed monitor makes its own measurements of power, so it can be used to detect erroneously high utility meter readings.

The challenges of manufacturing, advertising, selling, and shipping monitors in consumer product quantities – for example, a million units per year, or 2800 units per day – are significant. Therefore, my expected go-to-market (GTM) strategy will be to partner with an established U.S. manufacturing company having proven manufacturing, sales, logistics, and marketing capabilities on this scale. In April, after filing a patent application (as discussed below), I began contacting manufacturers, but I wasn't able to identify a partner before submitting this proposal. The product will be initially sold in online markets, like Amazon. When a sufficient record of production and online sales is achieved, the product can be introduced into brick-and-mortar retail stores, like Walmart.

Soliciting prospective manufacturing partners involves disclosing design details, which, without IP protection, could risk loss of ownership. Therefore, before contacting any manufacturers, I filed USPTO patent application 19/078,894[7] on the presently known novel aspects of the sensor. A continuation or a continuation-in-part can be filed with the USPTO before the first patent issues to protect any additional innovative aspects developed during the proposed project. I chose this IP strategy because, while the proposed device could be reverse-engineered and copied, infringement would be easy to discover. The patent(s) will constitute a legal monopoly for the assignee, and a strong barrier to entry for competitors, for about twenty years. $6500.00 in TABA funds are requested in the budget for assistance with prosecuting and securing intellectual property protection.

To further mitigate concerns about market demand and marketing staff, we can commission from Finish Line an independent Market Validation study. This will directly address the question "Will People Buy This Product?" and could also help to confirm requirements for parameters such as accuracy, radio range, and battery life. An independent Go to Market (GTM) study can address the question "How Will the Product go to Market?" in more detail. Finish Line routinely conducts such studies for startups.

Because it has no contact with high-voltage conductors, the whole-house monitor shouldn't incur any significant regulatory or safety certification testing costs. However, it would be prudent to have an accredited electrical safety laboratory conduct a review to authoritatively establish this in Phase II.

No outside funding, other than NSF Seed Fund funding, has yet been sought or received for this project.

A major concern expressed by the review panel was that there were no letters of support. Since the latest NSF Program Solicitation now explicitly prohibits such letters of support, this concern is eliminated.